Baryon Resonances in Chiral Dynamics

D. Jido (YITP, Kyoto)

Introduction

Photoproduction of Baryon resonances

hyperon resonances

One of the important physics in the LEPS2 experiments will be photoproduction of baryon resonances, especially production of baryon resonances with a strange quark.

Introduction

Photoproduction of Baryon resonances

hyperon resonances

Main goal in quark nuclear physics

understanding of hadron properties in aspect of QCD

Keywords to link hadrons to QCD

symmetries in QCD

Our main goal in quark nuclear physics is to understand structures and dynamics of hadrons in the aspect of QCD. To make a bridge from hadrons to QCD, important keywords may be symmetries in QCD, which are flavor symmetry and chiral symmetry.

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symmetries in QCD

- Flavor Symmetry $m_u = m_d = m_s$
- Chiral Symmetry $m_u = m_d = m_s = 0$

The complete flavor symmetry is achieved if up, down and strange quarks have the same mass, while, the exact chiral symmetry is realized if the quarks are massless.

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- Chiral Symmetry $m_u = m_d = m_s = 0$

Importance of explicit breaking in baryon resonances

In this talk, we would like to see that explicit symmetry breaking of both flavor and chiral symmetries is important, if we take the meson-baryon picture for the baryon resonances,

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Importance of explicit breaking in baryon resonances

$\longrightarrow$ help us to understand structure of resonance

and we also see that systematic studies of the effects of the symmetry breaking will help us to understand the structure of the baryon resonances.

Flavor Symmetry

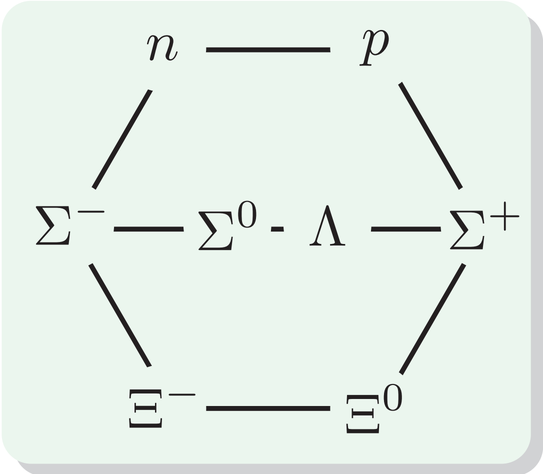
Gell-Mann Okubo Mass Formula

Octet baryon (N, Λ, Σ, Ξ)

$$m_\Sigma - m_N = \frac{1}{2}(m_\Xi - m_N) + \frac{3}{4}(m_\Sigma - m_\Lambda)$$

254 MeV   248 MeV

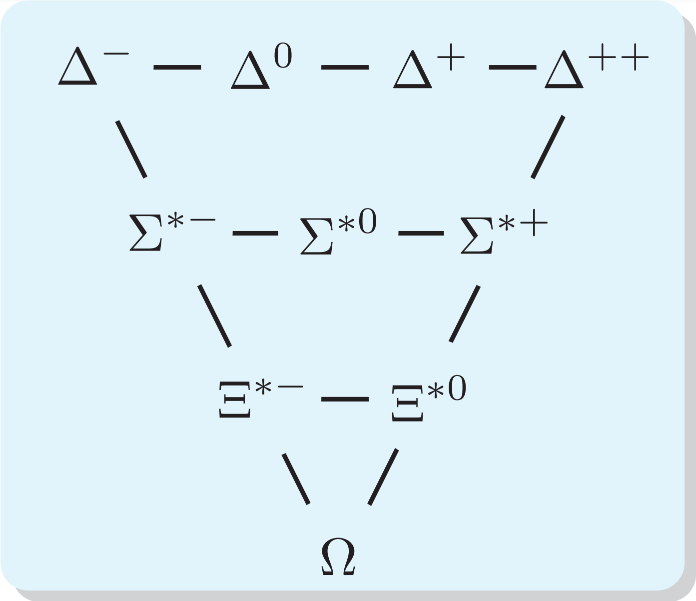
3% level agreement



Decuplet baryon (Δ, Σ*, Ξ*, Ω)

$$m_{\Sigma^*} - m_\Delta = m_{\Xi^*} - m_{\Sigma^*} = m_\Omega - m_{\Xi^*}$$

152 MeV   149 MeV   139 MeV



First of all, let us start with discussion on the flavor symmetry in the ground state baryons. If the flavor symmetry is good with a small breaking, the effect of the symmetry breaking can be treated as a perturbation.

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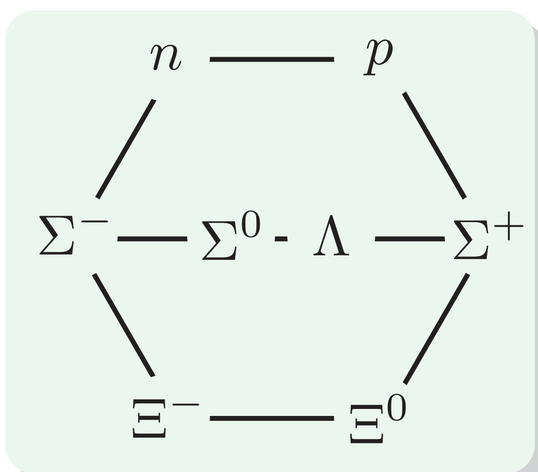

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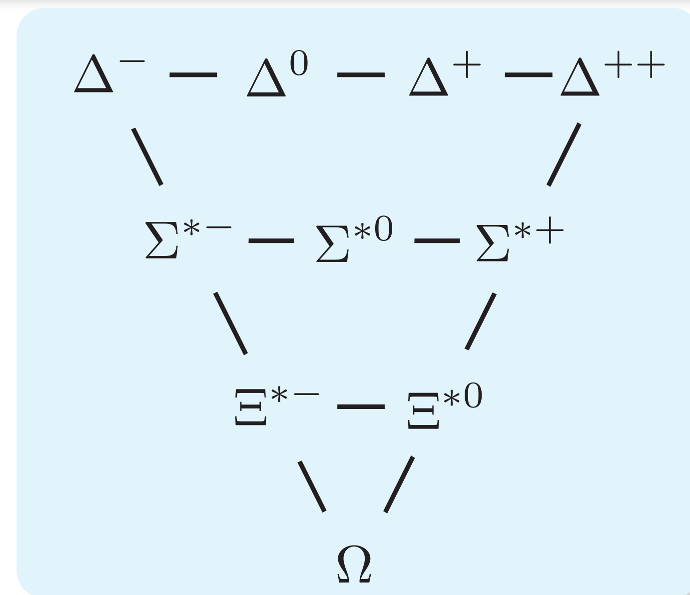

The good examples of the perturbative treatment are the mass spectra of the octet and decuplet baryons, in which the Gell–Mann Okubo mass formula is satisfied well. For the octet baryons, the left hand side of the mass formula is 254 MeV, while the right hand side is 248 MeV.

Flavor Symmetry

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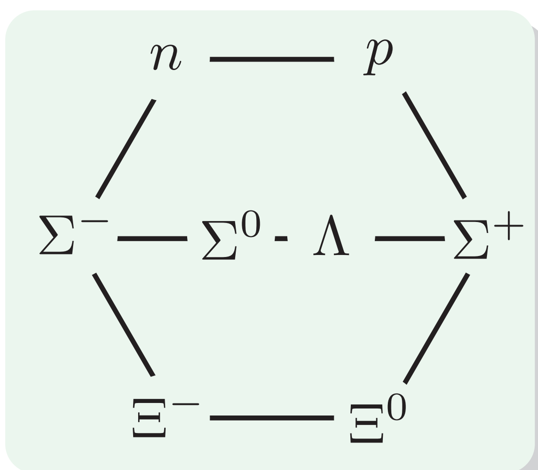

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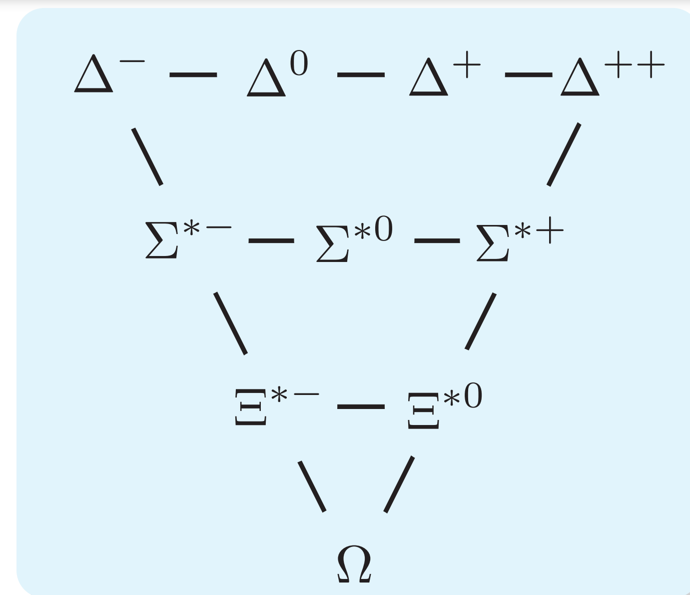

This is 3% level of agreement. The decuplet baryons also satisfy the Gell-Mann Okubo mass formula, which is a relation for the mass differences.

Flavor Symmetry

Gell-Mann Okubo Mass Formula

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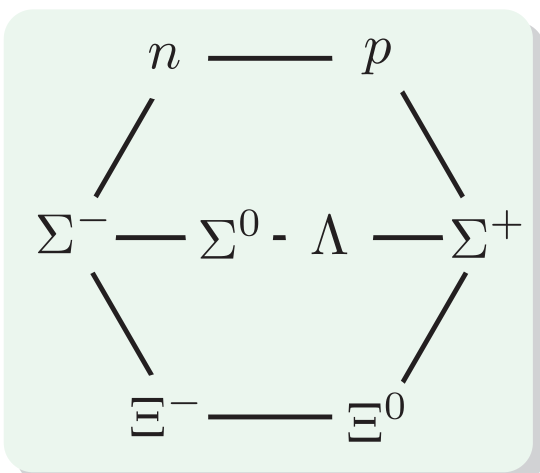

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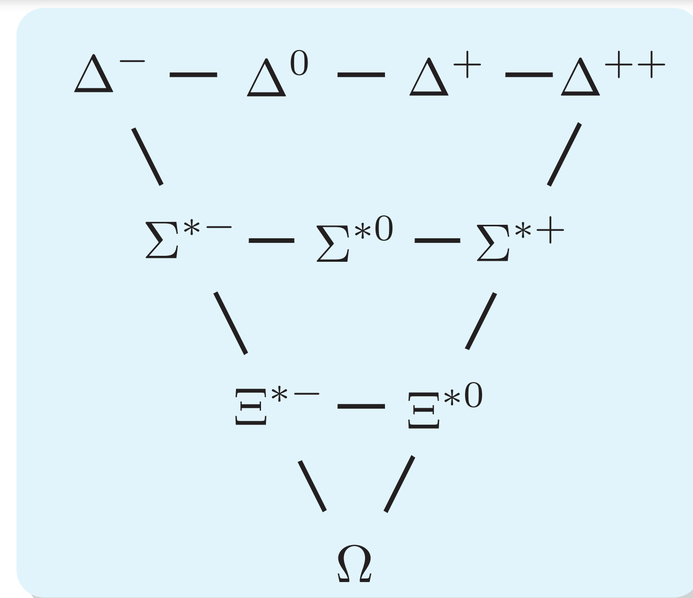

Typical mass scale >> SU(3) breaking

This remarkable agreement comes from that the SU(3) breaking scale, which is a few hundred MeV, is much smaller than the typical baryon mass scale, 1 GeV.

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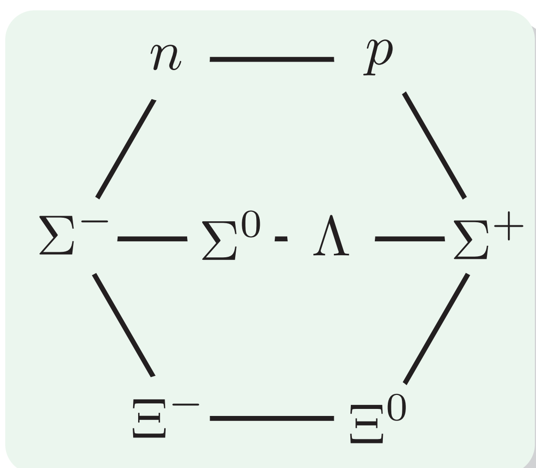

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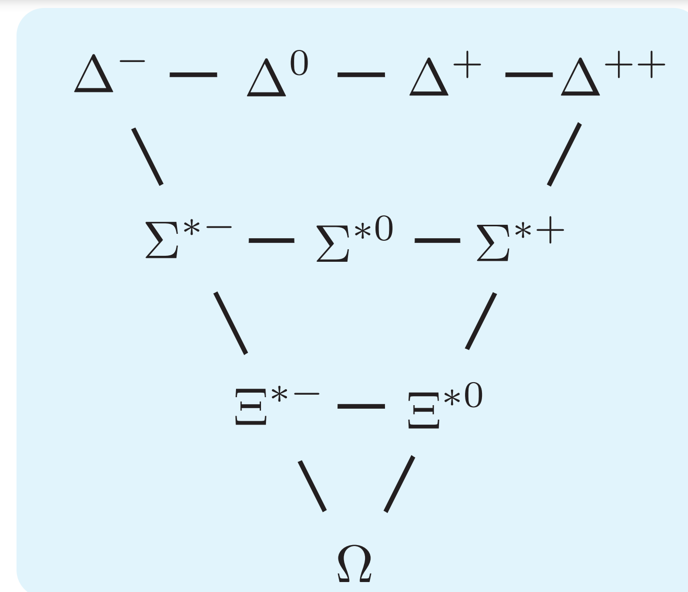

Typical mass scale >> SU(3) breaking

Genuine quark origin ??

Quark model, Large Nc, chiral effective theory

The other interesting point is that these baryons are described well in the quark model and are usually treated as fundamental fields in chiral effective theory. This would suggest that these baryons could be composed largely by genuine quark components.

Flavor Symmetry

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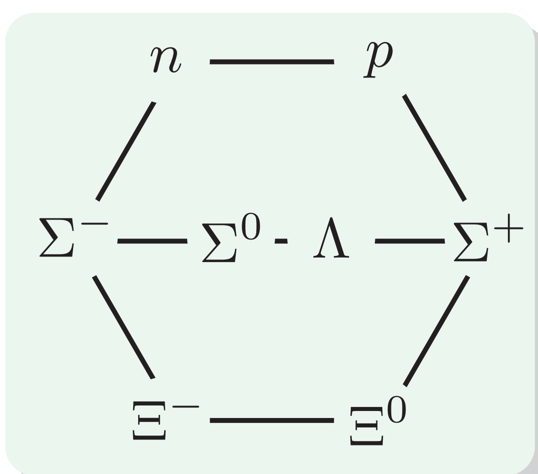

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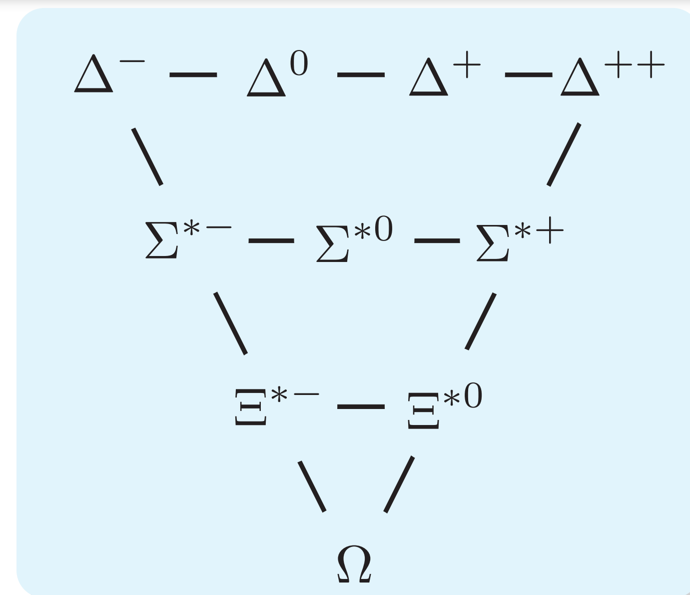

Typical mass scale >> SU(3) breaking

Genuine quark origin ??

Quark model, Large Nc, chiral effective theory

We will see later that, in the case of the baryon resonances, the SU(3) breaking effect is very large and essential to reproduce the mass spectrum, if we take meson-baryon quasi bound state picture for the baryon resonances.

Chiral Symmetry

exact with massless quarks

- massless NG bosons emerge with spontaneous breaking
- effective degrees of freedom

Chiral field: $U = \exp[i\phi \cdot \lambda / F]$

Chiral symmetry is exact if the quarks are massless. With spontaneous breakdown of chiral symmetry, massless Nambu Goldstone bosons emerge. The effective degrees of freedom is the chiral field expressed in a nonlinear form of the Nambu Goldstone field.

Chiral Symmetry

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effective degrees of freedom

Chiral field: $U = \exp[i\phi \cdot \lambda / F]$

another important feature

all interactions associated with chiral fields have derivatives.

$\longrightarrow$ interactions are weak in low energies
meson momenta be expansion parameter

Another important feature is, as a logical consequence, all the interactions associated with the chiral fields have derivatives. Thus the interactions to the Nambu Goldstone fields are weak in low energies. So the meson momenta can be an expansion parameter.

Chiral Symmetry

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effective degrees of freedom

Chiral field: $U = \exp[i\phi \cdot \lambda / F]$

another important feature

all interactions associated with chiral fields have derivatives.

$\longrightarrow$ interactions are weak in low energies
meson momenta be expansion parameter

explicit breaking as perturbation $m_q \ll m_N$

The explicit breaking of chiral symmetry due to the quark mass is also treated as perturbation, since the quark mass is much smaller than the typical energy scale, 1 GeV.

Chiral Symmetry

exact with massless quarks

massless NG bosons emerge with spontaneous breaking

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Chiral field: $U = \exp[i\phi \cdot \lambda / F]$

another important feature

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Chiral Perturbation Theory

This lead us to systematic expansions of the meson momenta and the quark masses, as summarized in the celebrated chiral perturbation theory.

Chiral Symmetry

exact with massless quarks

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explicit breaking as perturbation $m_q \ll m_N$

Chiral Perturbation Theory

two expansions are correlated $p^2 = m^2 = -2m_q \langle \bar{q} q \rangle / F^2$

Mathematically these expansions in terms of meson momenta and quark masses are independent, but these are correlated on the mass shell of the pion, since p^2 is equal to the meson mass and the meson mass is related to the quark mass by the GOR relation.

Chiral Symmetry

energy range where ChPT works

from threshold up to resonance region

The energy range where the chiral perturbation theory works is around the threshold energies, at most, up to the energy where resonances appear, since the resonances cannot be described by perturbation.

Chiral Symmetry

energy range where ChPT works

from threshold up to resonance region

to apply chiral effective theory to resonances

1) introduce new elementary field

2) generate resonance

To apply chiral effective theory for the resonance region, we have the following two ways: 1) we introduce a new field for the resonance as an elementary field, 2) we generate resonances dynamically with enough attraction by solving scattering equation.

Chiral Symmetry

energy range where ChPT works

from threshold up to resonance region

to apply chiral effective theory to resonances

1) introduce new elementary field

ex) decuplet baryons, Δ, Σ^*

genuine quark origin

2) generate resonance

In the first case, good examples are the decuplet baryons, such as Δ and Σ^*. In this case the origin of the resonance is something other than the meson-baryon dynamics, such as genuine quark origin.

Chiral Symmetry

energy range where ChPT works

from threshold up to resonance region

to apply chiral effective theory to resonances

1) introduce new elementary field

ex) decuplet baryons, Δ, Σ^*

genuine quark origin

2) generate resonance

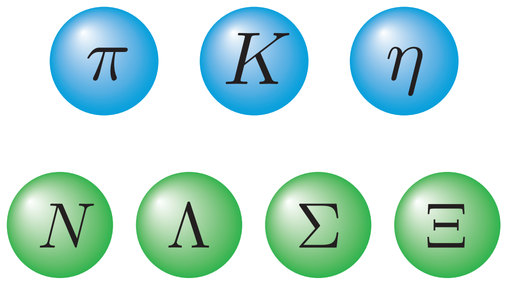
ex) s-wave resonances, $\Lambda(1405)$

quasi bound state of meson and baryon

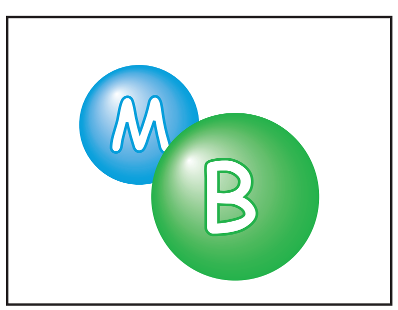
In the second case, the resonance is formed as a meson-baryon quasi bound state within the chiral dynamics, such as $\Lambda(1405)$. To formulate the second picture, we introduce the chiral unitary approach.

Chiral Unitary Model

Fundamental degrees of freedom



s-wave baryon resonance

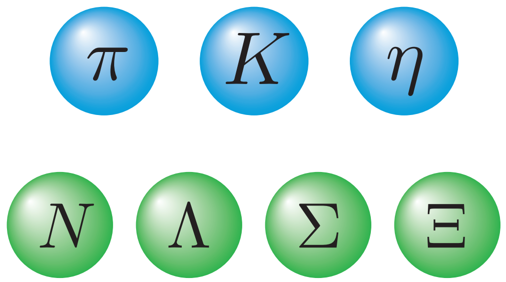


Quasi bound state
of meson + baryon

I explain briefly the chiral unitary model. In the chiral unitary model, the Nambu Goldstone bosons and the octet baryons are fundamental degrees of freedom, and the baryon resonances are described as a quasi-bound state of meson and baryon.

Chiral Unitary Model

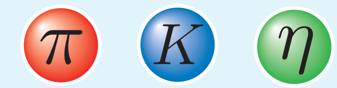
Fundamental degrees of freedom



Chiral perturbation theory

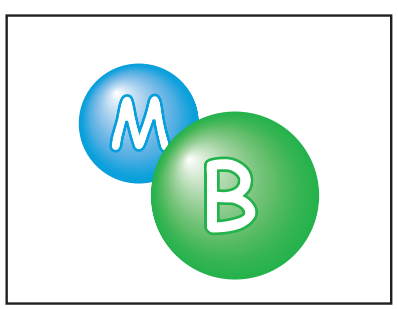
effective theory of QCD at low energies

dynamics of Nambu-Goldstone bosons



meson-baryon interactions are constrained by chiral symmetry in QCD

s-wave baryon resonance

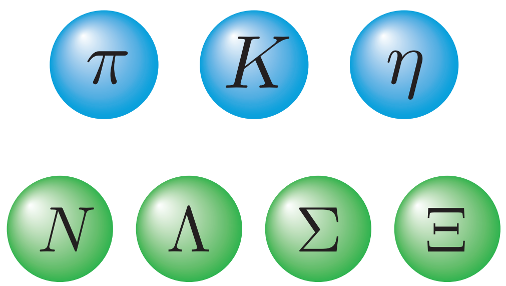


Quasi bound state of meson + baryon

The basic dynamics of meson and baryon in low energies are given by the chiral perturbation theory.

Chiral Unitary Model

Fundamental degrees of freedom



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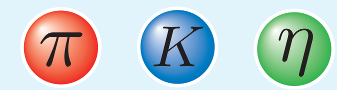
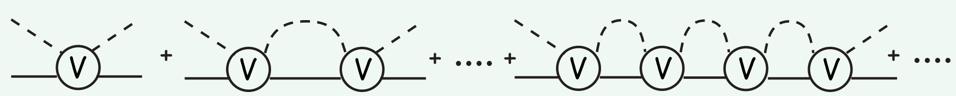


meson-baryon interactions are constrained by chiral symmetry in QCD

Unitary condition on scattering amplitude

summing up series of some diagrams non-perturbatively
in a way guided by the well-established procedure in 60's.

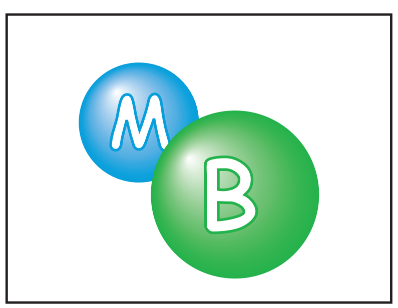
N/D method
Lippmann–Schwinger eq.,
Bethe–Salpeter eq.



$$T = V + VGT$$

$$T = \frac{1}{1 - VG} V$$

s-wave baryon resonance

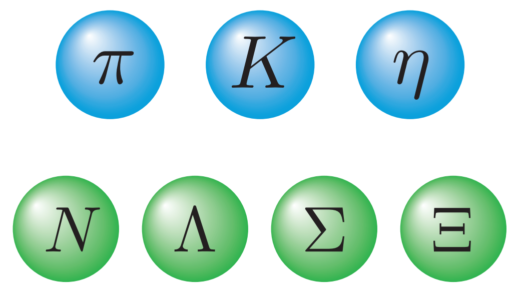


Quasi bound state
of meson + baryon

With the low energy elementary vertex as a building block, we impose unitarity condition on the scattering amplitude. This is just to solve the scattering equation, namely Lippmann–Schwinger or Bethe–Salpeter equation.

Chiral Unitary Model

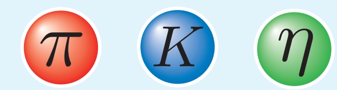
Fundamental degrees of freedom



Chiral perturbation theory

effective theory of QCD at low energies

dynamics of Nambu-Goldstone bosons



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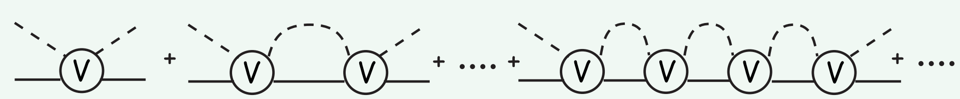

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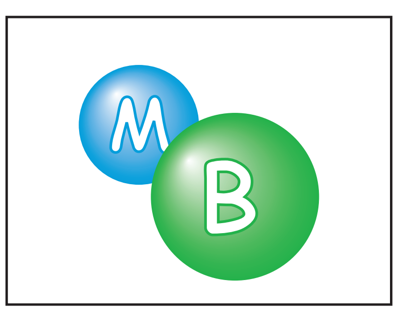


Quasi bound state of meson + baryon

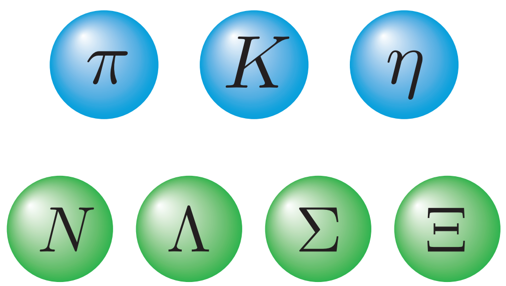
expressed as a pole of scattering amplitude

$$T_{ij} \simeq \frac{g_i g_j}{E - M_R + i\Gamma_R/2}$$

Then the resonance is dynamically generated in the scattering amplitude and is expressed as a pole of the amplitude.

Chiral Unitary Model

Fundamental degrees of freedom



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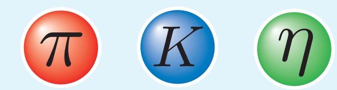

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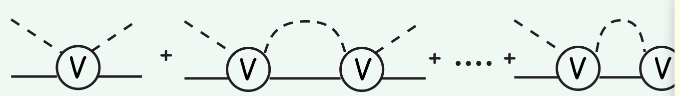
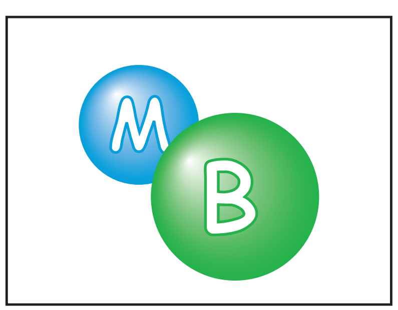


$$T = V + VGT$$

$\lvert g_{ii}\rvert^2$ in particle basis				
Pole	$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$K\Xi$
$1390 - 66i$	4.5	8.4	0.59	0.38
$1426 - 16i$	7.3	2.3	2.0	0.13
$1680 - 20i$	0.62	0.074	1.1	12

Λ channel (S=-1, I=0)

s-wave baryon resonance



Quasi bound state
of meson + baryon

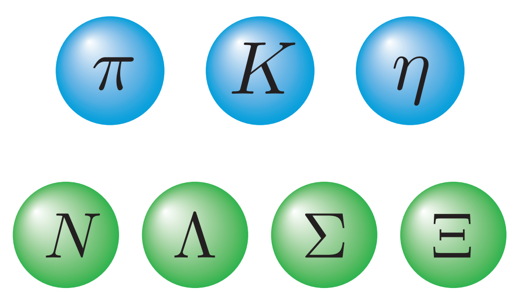
expressed as a pole of scatt

$$T_{ij} \simeq \frac{g_i g_j}{E - M_R + i\Gamma_R/2}$$

The mass and width of the resonance are obtained as the pole position in the chiral unitary model, and the coupling constants to the scattering channels are calculated as the residua of the pole.

Chiral Unitary Model

Fundamental degrees of freedom



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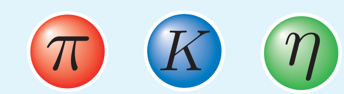

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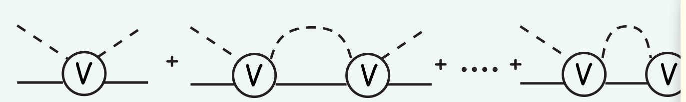

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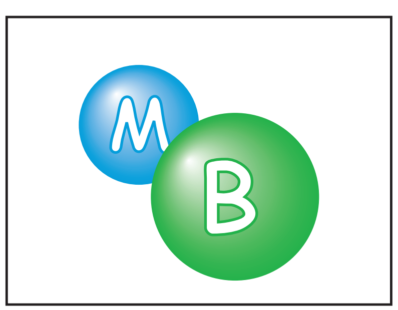


Quasi bound state of meson + baryon

expressed as a pole of scatt

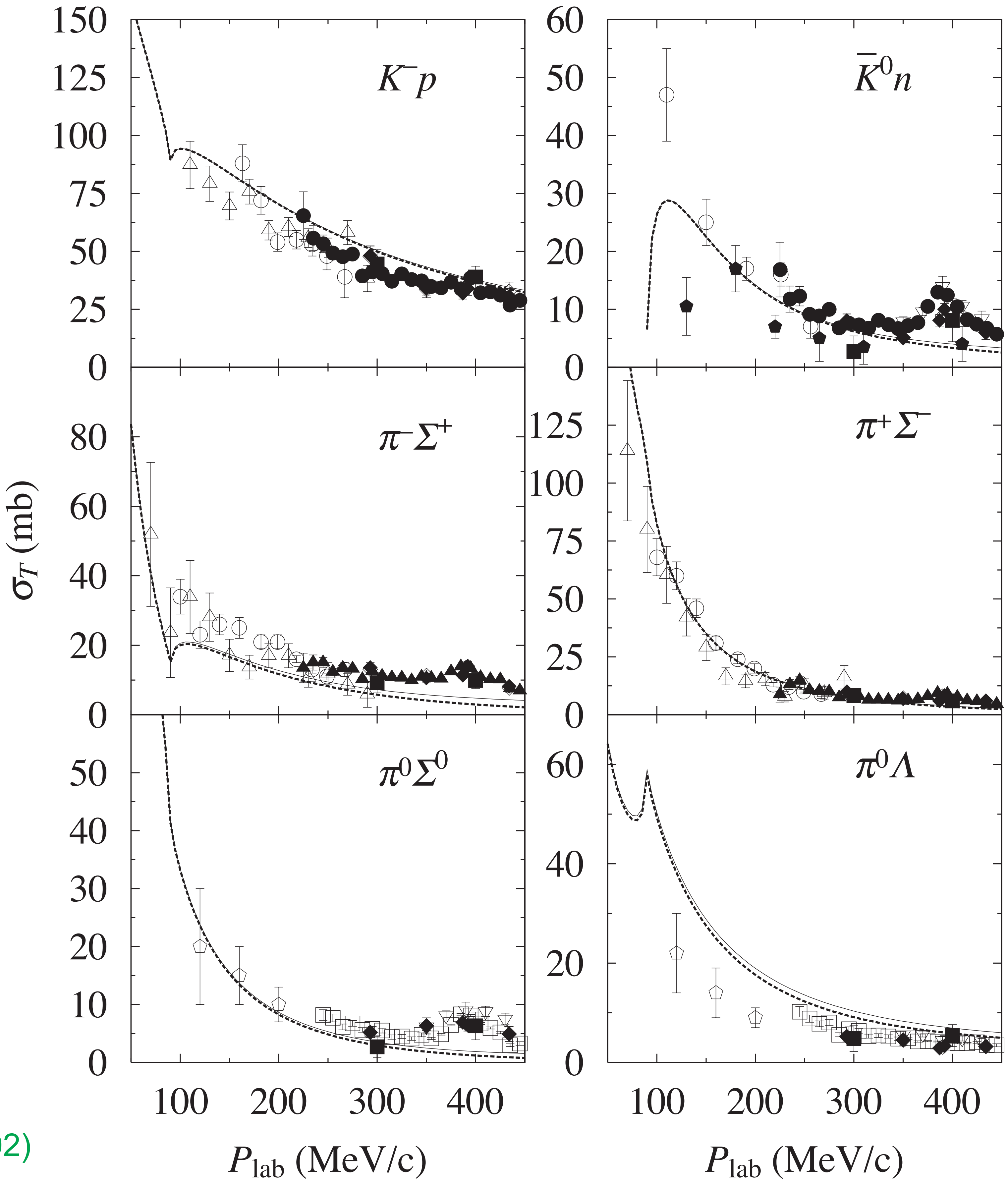
$$T_{ij} \simeq \frac{g_i g_j}{E - M_R + i\Gamma_R/2}$$

It is very interesting that the first pole for Λ(1405) couples strongly to the πΣ channel and the second couples strongly to the KN channel, which is indeed above the Λ(1405) and a closed channel.

Comparison with experiments

Total cross sections

$K^- p \rightarrow$ various channels



Chiral unitary model
with Tomozawa-Weinberg term

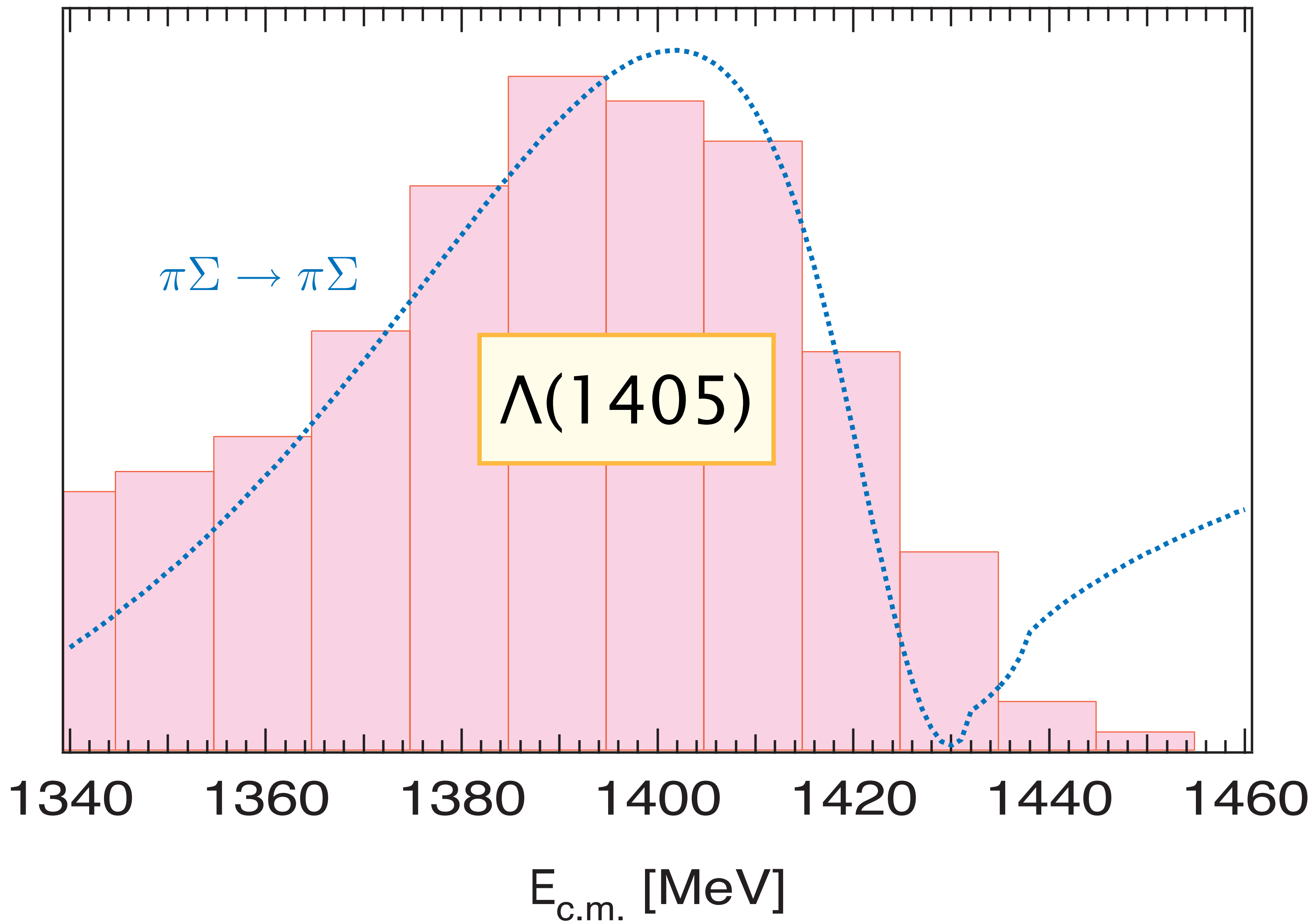
Oset, Ramos NPA635, 99 (98)
Jido, Oset, Ramos, PRC66, 055203 (02)

Comparison with experiments

$$\frac{d\sigma}{dM} = C \left| T^{I=0}_{\pi\Sigma\to\pi\Sigma} \right|^2 q_{\mathrm{c.m.}}$$

Mass distribution

$\pi\Sigma \to \pi\Sigma \quad (I = 0)$



Oset, Ramos NPA635, 99 (98)
Jido, Oller, Oset, Ramos, Meißner, NPA725, 181 (03)

Comparison with experiments

Photoproduction of $\Lambda(1405)$

$\gamma p \to K^+ (\Sigma\pi)^0$ SPring8/LEPS

Invariant mass spectra of $\pi^+\Sigma^-$ and $\pi^-\Sigma^+$

- not have definite isospin, partial waves

  interferences of

  continuum background $\pi\Sigma$ I=0, 1, 2

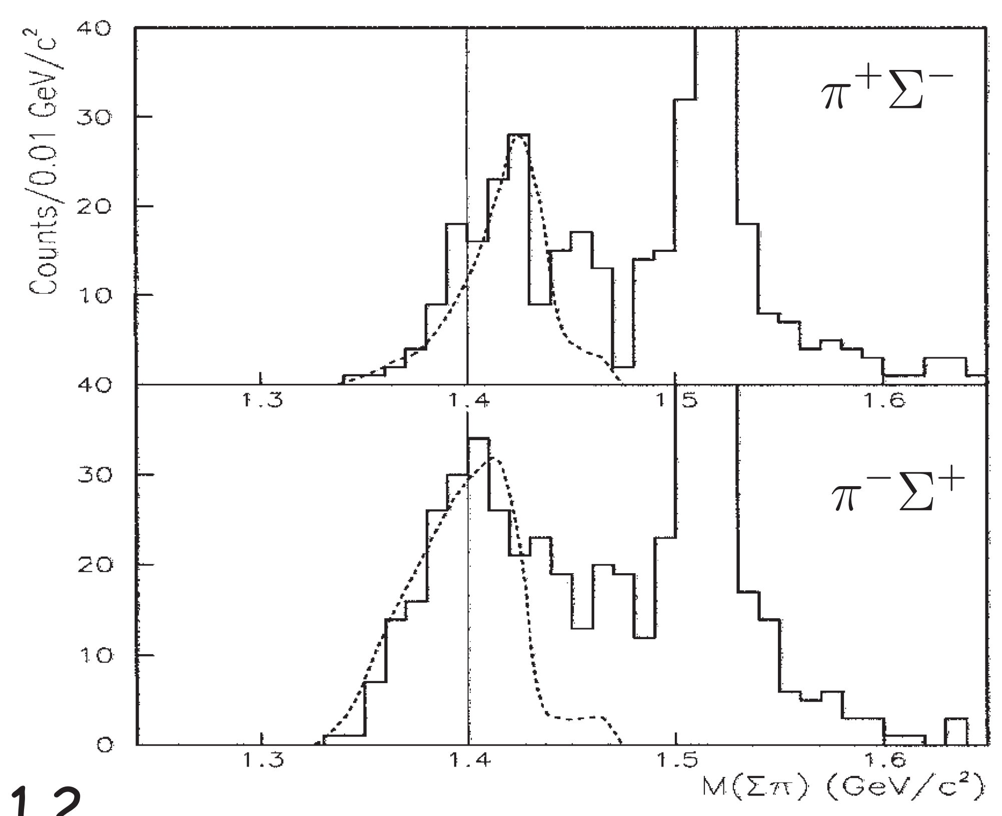
  resonances $\Lambda(1405)$ and $\Sigma(1385)$

- $\Sigma(1385)$ $3/2^+$ I=1

  decays to $\pi^\pm\Sigma^\mp$ with 12%

Experimentally seen in the figures is
interference of $\Lambda(1405)$ and continuum $\pi\Sigma$ with I=0,1,2

J.K. Ahn, NPA721, 715c (2003) SPring8/LEPS



Chiral unitary approach

- p-wave ($\Sigma(1385)$ resonance) is not important in these energies.

  Jido, Oset, Ramos, PRC66, 055203 (2002)

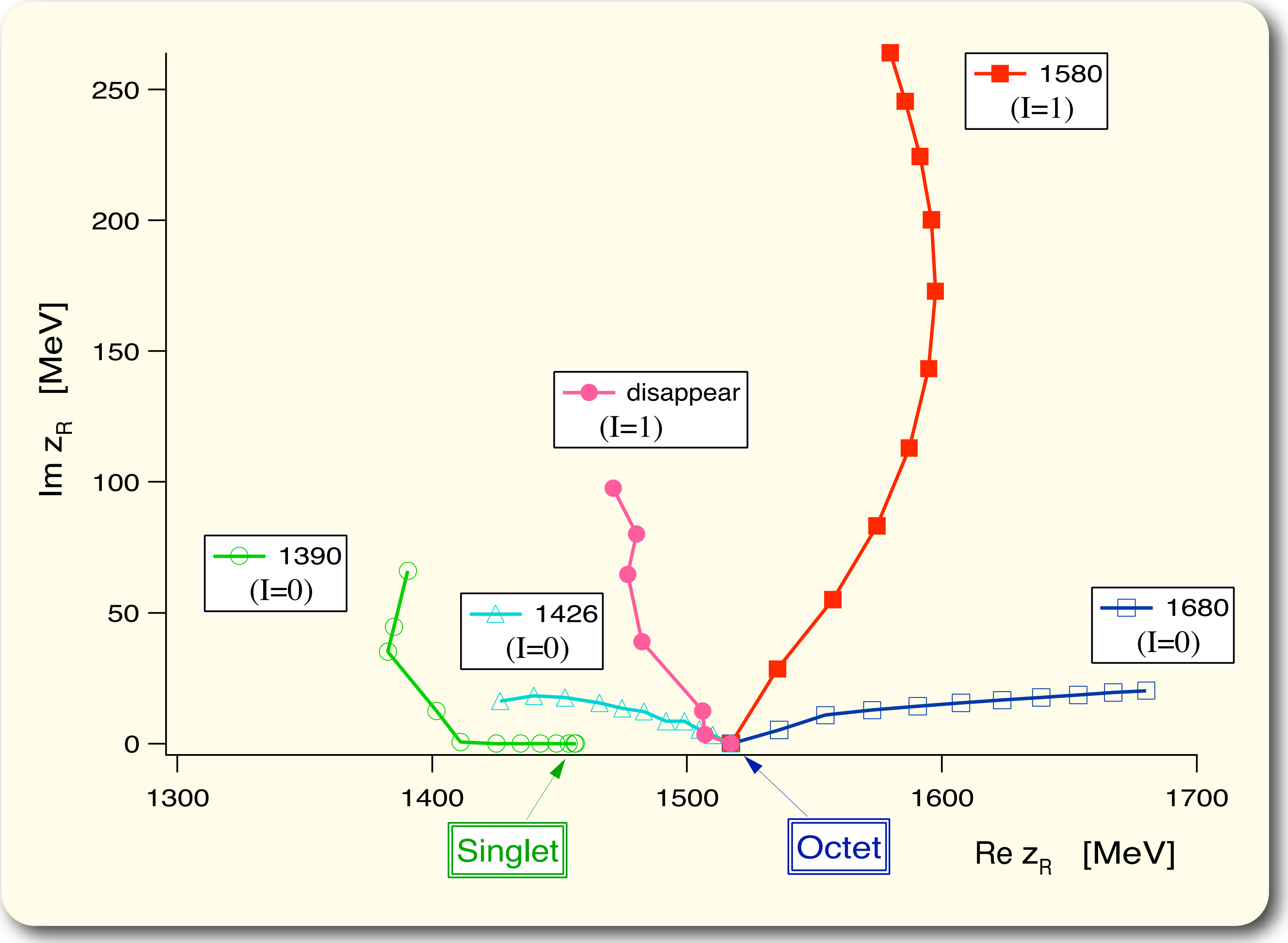
- Chiral unitary model reproduces these spectra very well.

  J.C. Nacher, et. al. PLB455, 55 (1999) **prediction !**

Therefore the chiral unitary approach gives us very good description both for the $\Lambda(1405)$ resonance and the background continuum.

Flavor Symmetry

Trajectories of poles
from SU(3) limit to physical world

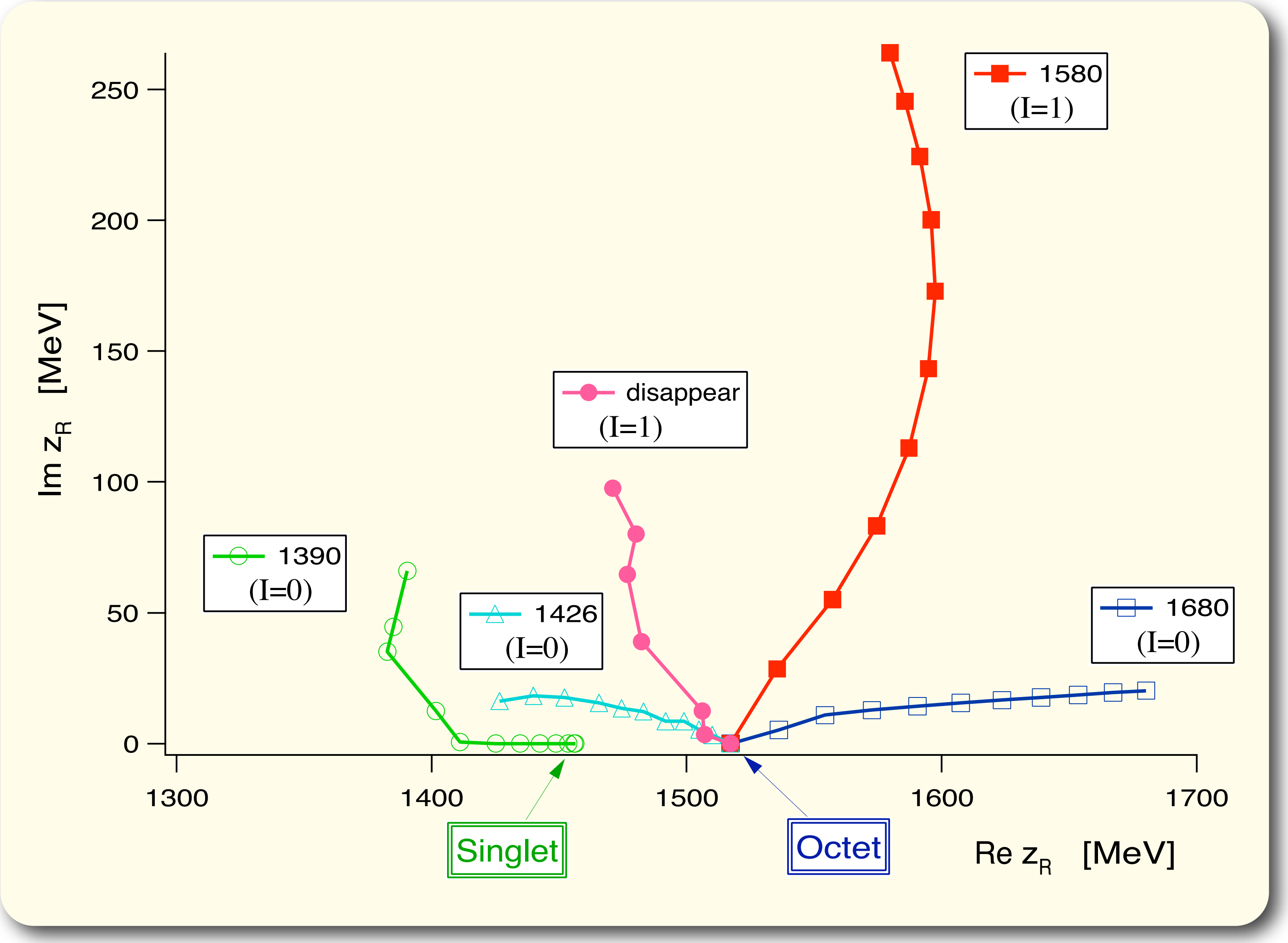


This plot shows that trajectories of the pole positions in the meson-baryon scattering amplitudes with S=−1 from the SU(3) symmetric limit to the physical world. The horizontal line shows the mass of the resonance and the vertical line shows the width.

Flavor Symmetry

Trajectories of poles
from SU(3) limit to physical world

Two bound states in SU(3) limit
singlet and octet channels



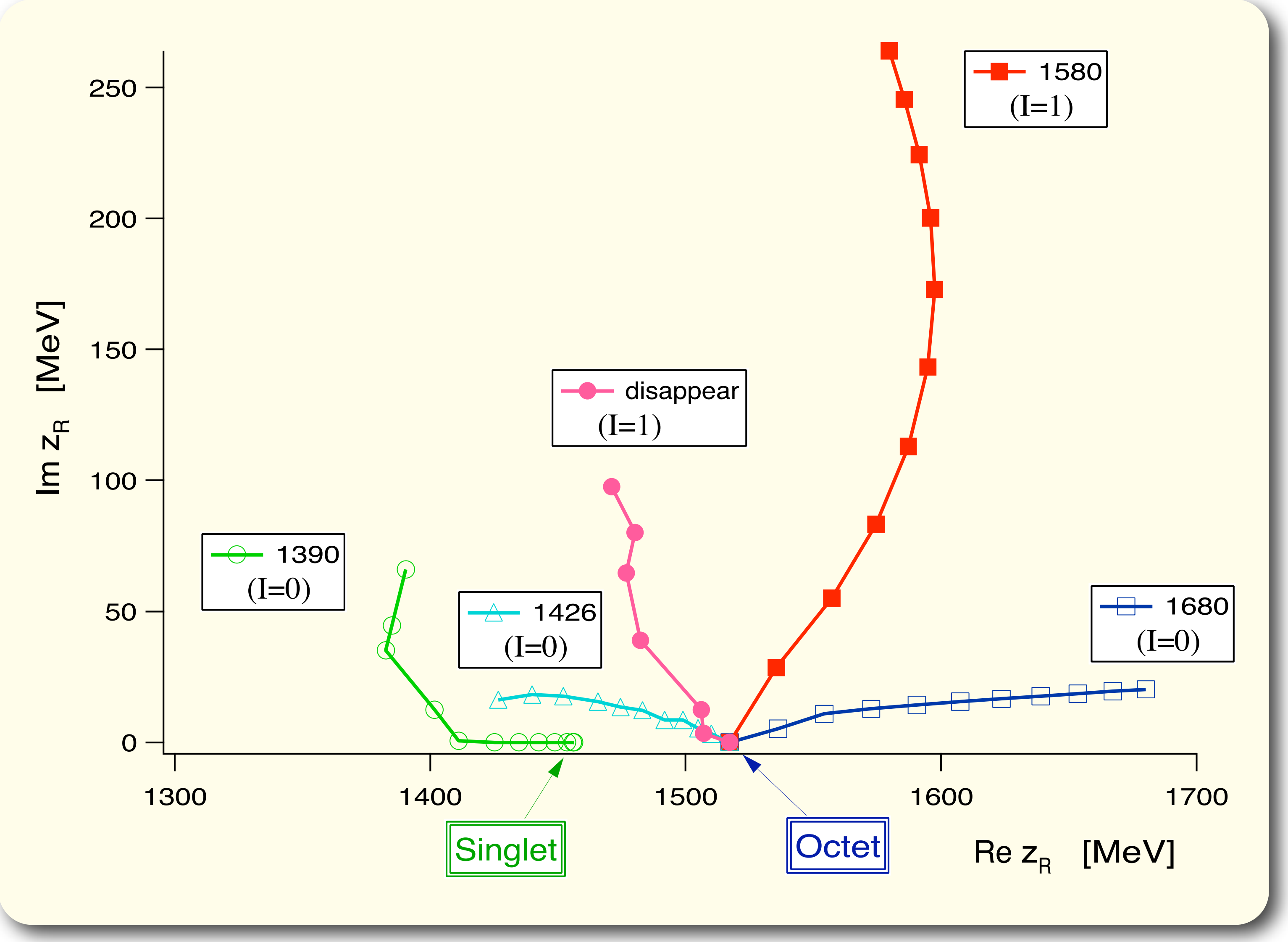
In this model, two bound states are generated for the singlet and octet channels in the SU (3) limit, where these channels are decoupled completely and the bound states are obtained by just solving single channel problem, since the threshold degenerate.

Flavor Symmetry

Trajectories of poles
from SU(3) limit to physical world

Two bound states in SU(3) limit
singlet and octet channels

Large SU(3) breaking
in baryon resonances



By changing the meson and baryon masses gradually to their physical values, the pole positions spread out in the complex plane. The SU(3) symmetry is largely broken in the baryon resonances.

Flavor Symmetry

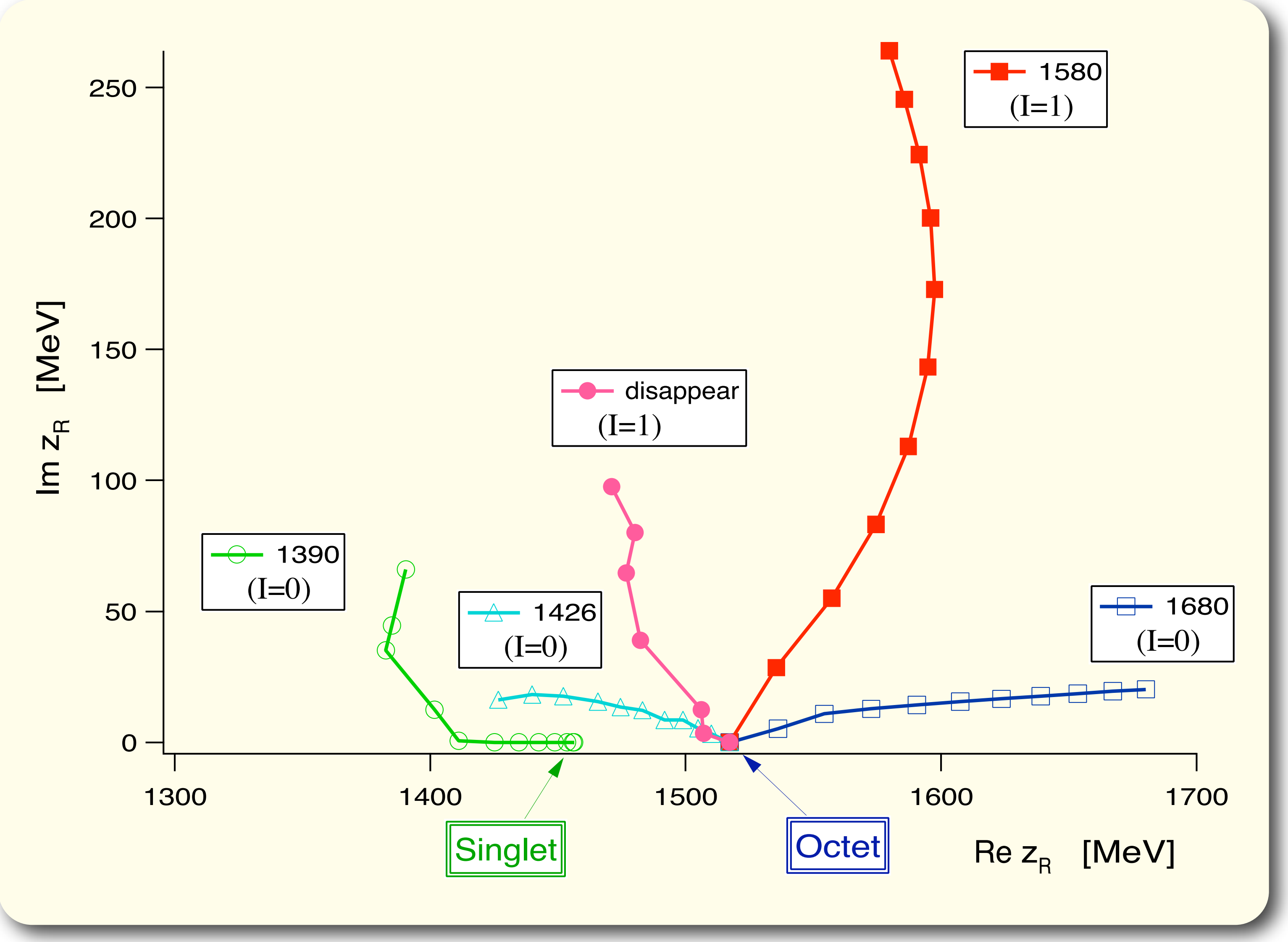
Trajectories of poles
from SU(3) limit to physical world

Two bound states in SU(3) limit
singlet and octet channels

Large SU(3) breaking
in baryon resonances

scattering amplitude

$$T = \frac{1}{1 - VG} V$$



In the present calculation, the amplitudes are obtained by solving the scattering equation with the lowest order term of the chiral expansion as a building block.

Flavor Symmetry

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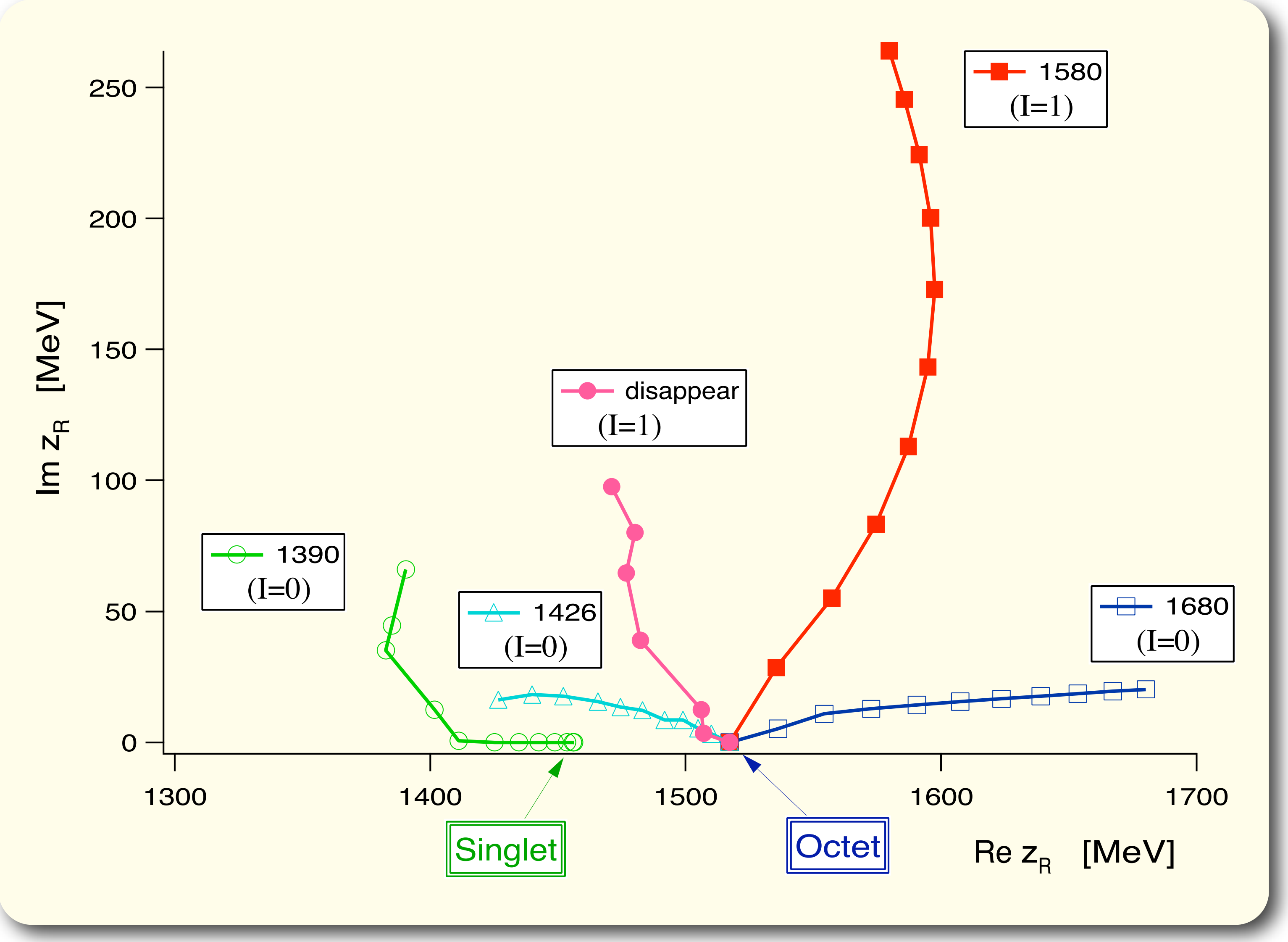
scattering amplitude

$$T = \frac{1}{1 - VG} V$$

V: WT term, SU(3) symmetric

G: loop function, SU(3) breaking



The lowest order term of the chiral perturbation theory, the Weinberg-Tomozawa term, V, is SU(3) invariant, while the loop integral is not, where we use the physical masses of the baryons and mesons.

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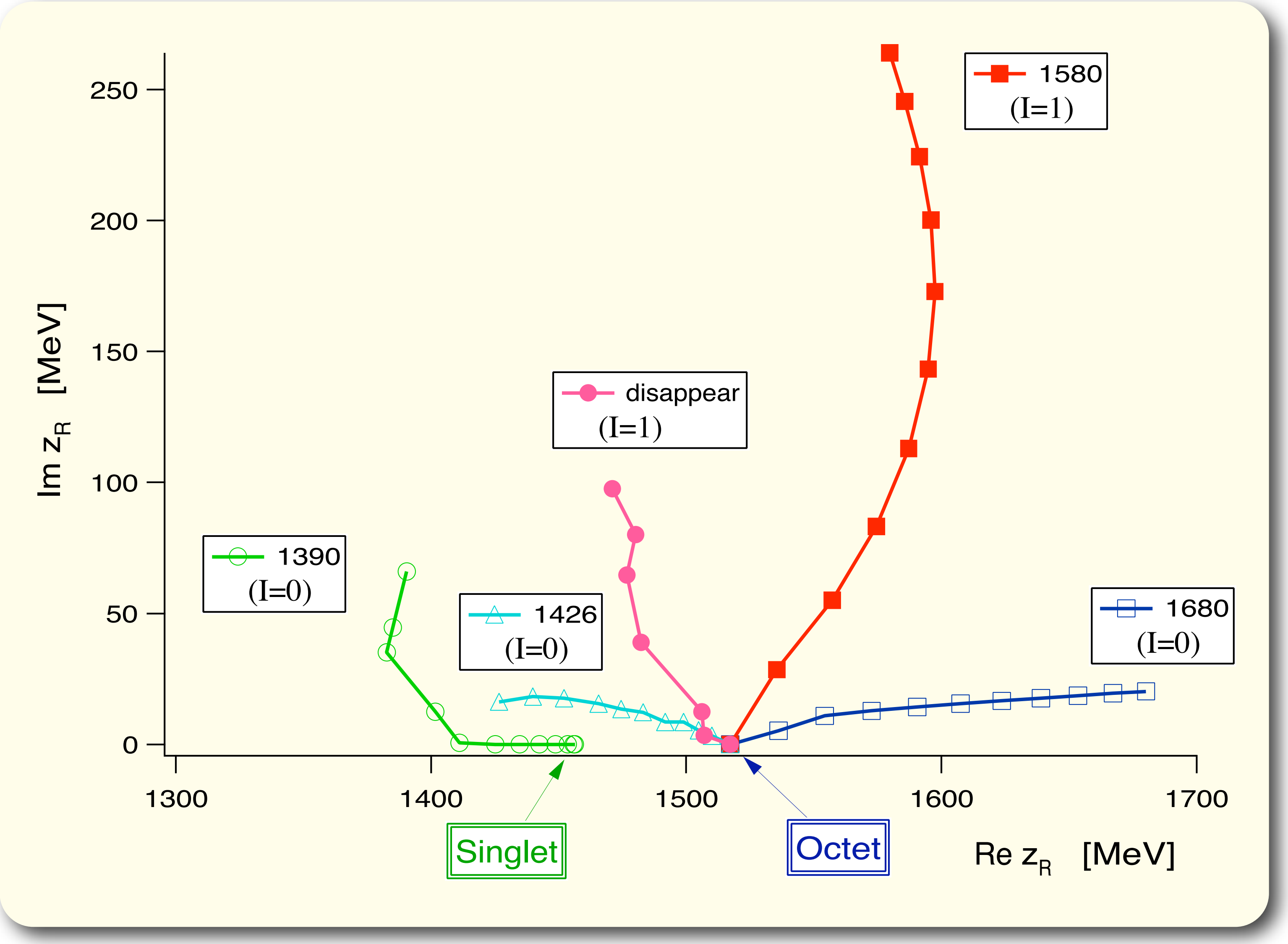

This is because the thresholds should be at the right positions to take into account of the proper phase space of the meson-baryon dynamics. Therefore the SU(3) breaking effect is essential in dynamical problems to obtain the baryon resonances in the right positions.

Flavor Symmetry

Trajectories of poles
from SU(3) limit to physical world

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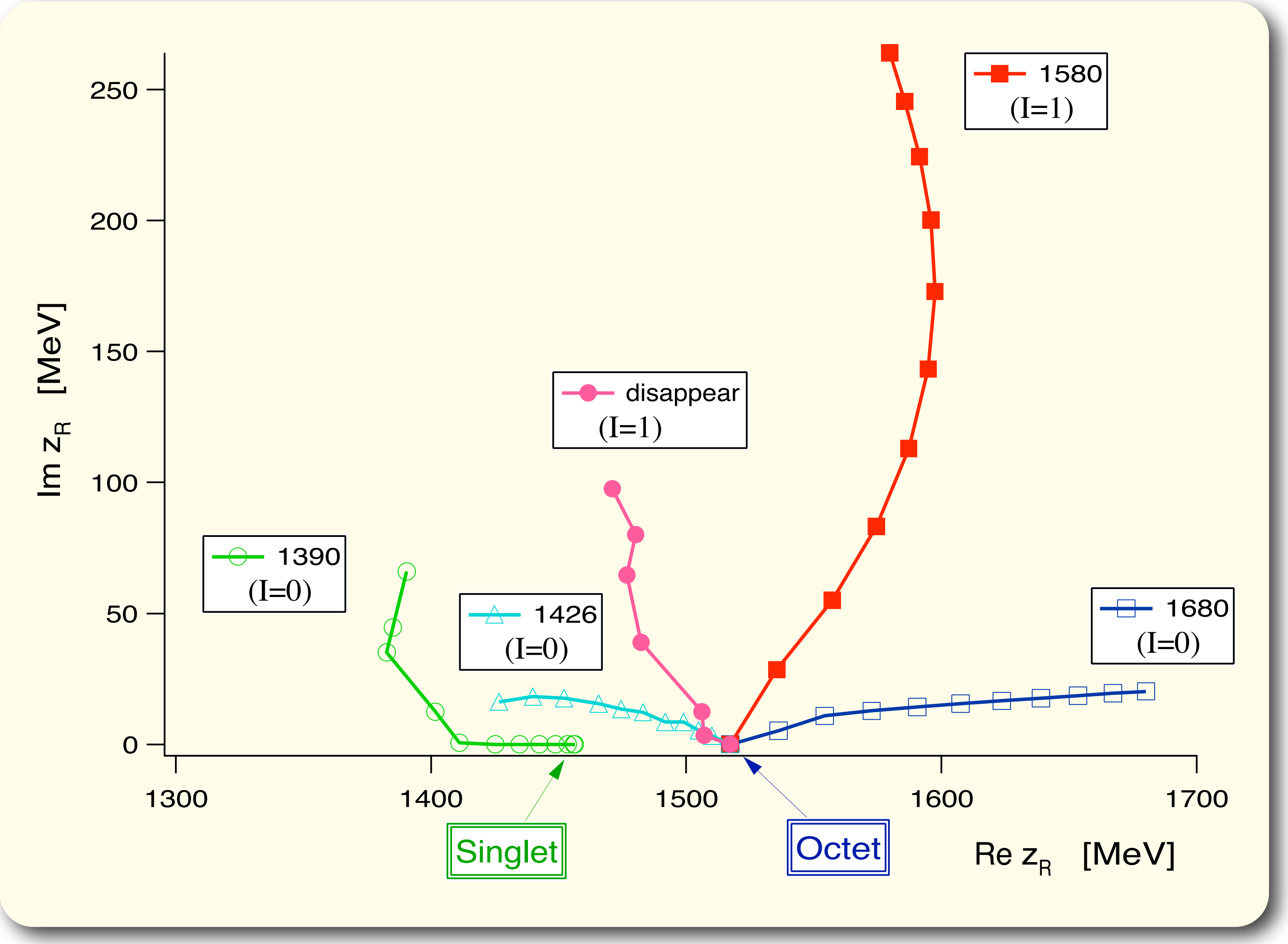

What I want to emphasize is that, if the meson-baryon quasi bound state picture is correct for the baryon resonances, the SU(3) breaking effect is essential and largely broken in the spectra of the baryon resonances.

Flavor Symmetry

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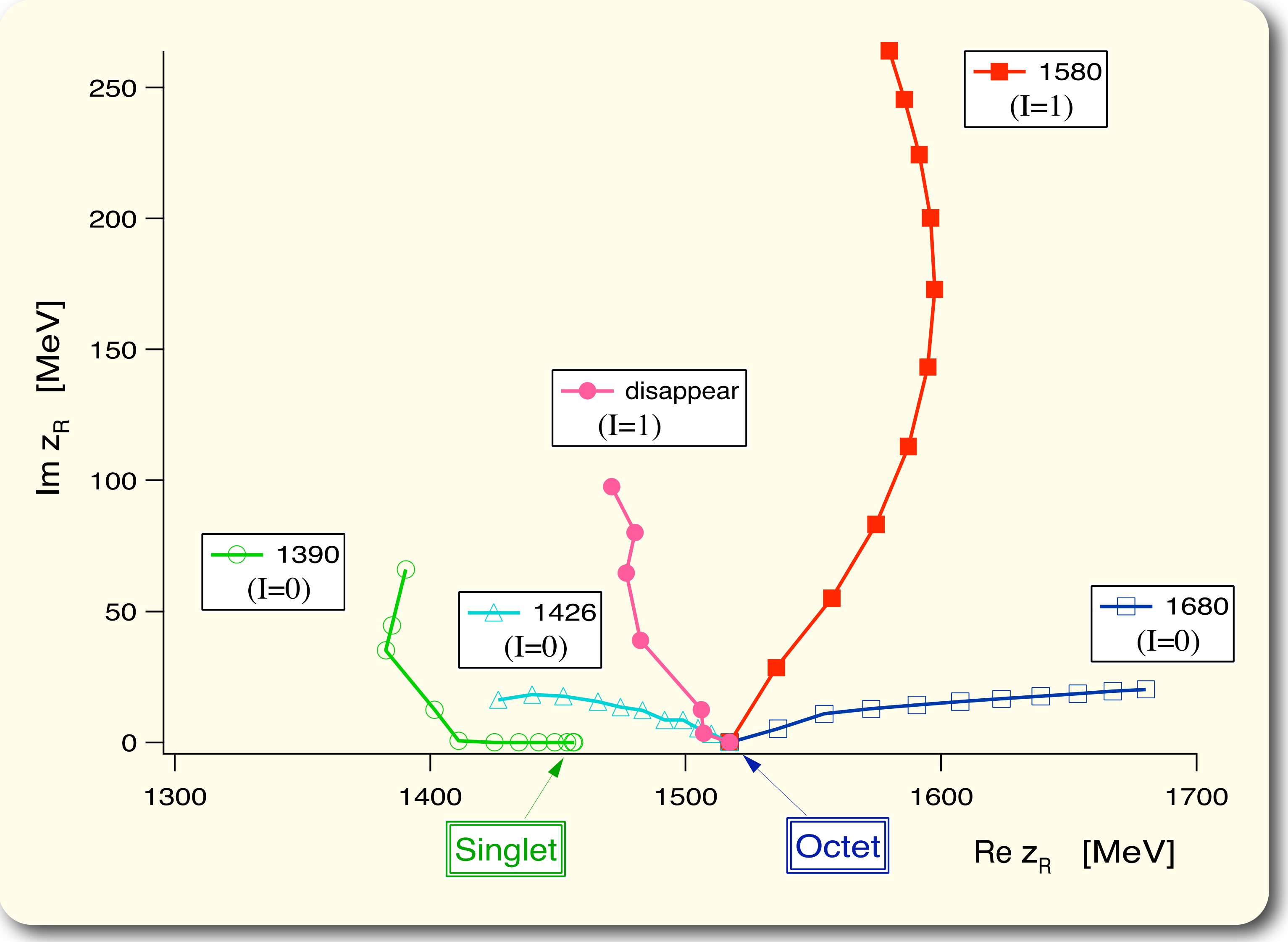

Binding energies in SU(3) limit

$$B_1 \simeq 70 \ \text{MeV}$$

$$B_8 \simeq 5 \ \text{MeV}$$

This is understood also by the fact that the binding energies in the SU(3) limit, which are calculated again in the chiral unitary model, are obtained as 70 MeV for the singlet channel and 5 MeV for the octet channels.

Flavor Symmetry

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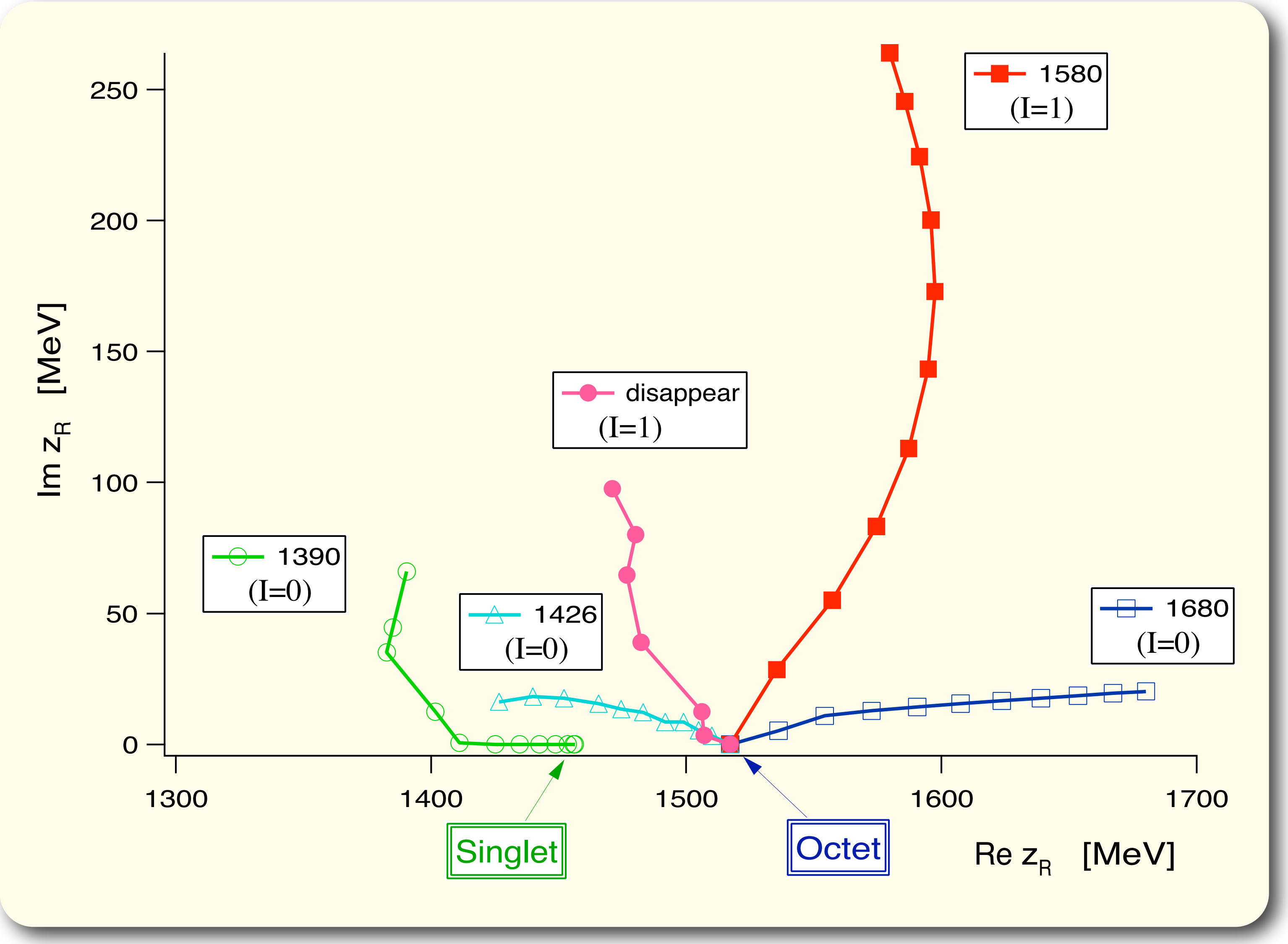

Binding energies in SU(3) limit

$$B_1 \simeq 70 \ \ \mathrm{MeV}$$

$$B_8 \simeq 5 \ \ \mathrm{MeV}$$

They are small in comparison with the SU(3) breaking scale, a few hundred MeV in the ground state baryon.

Flavor Symmetry

Trajectories of poles
from SU(3) limit to physical world

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singlet and octet channels

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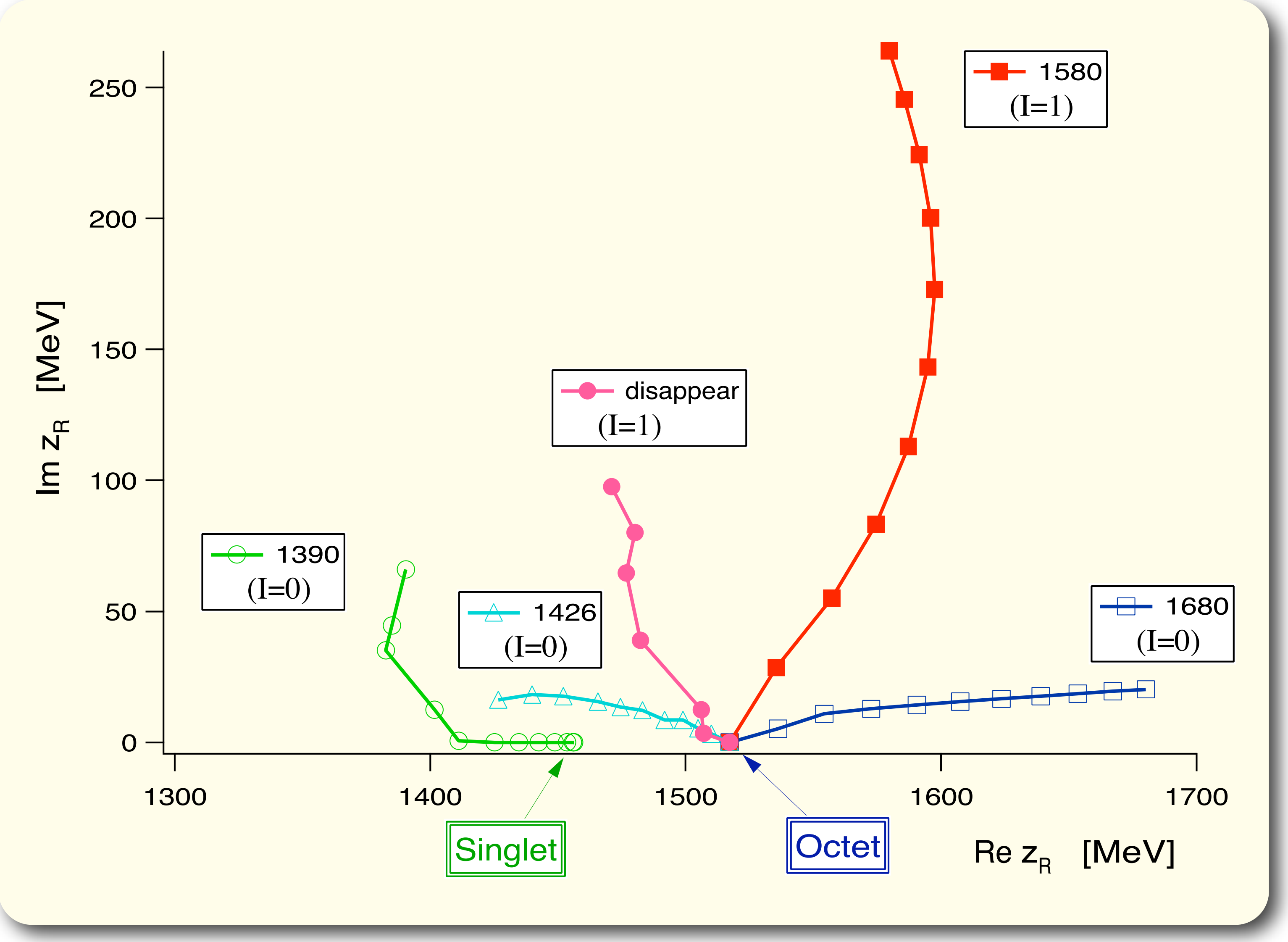


Binding energies in SU(3) limit

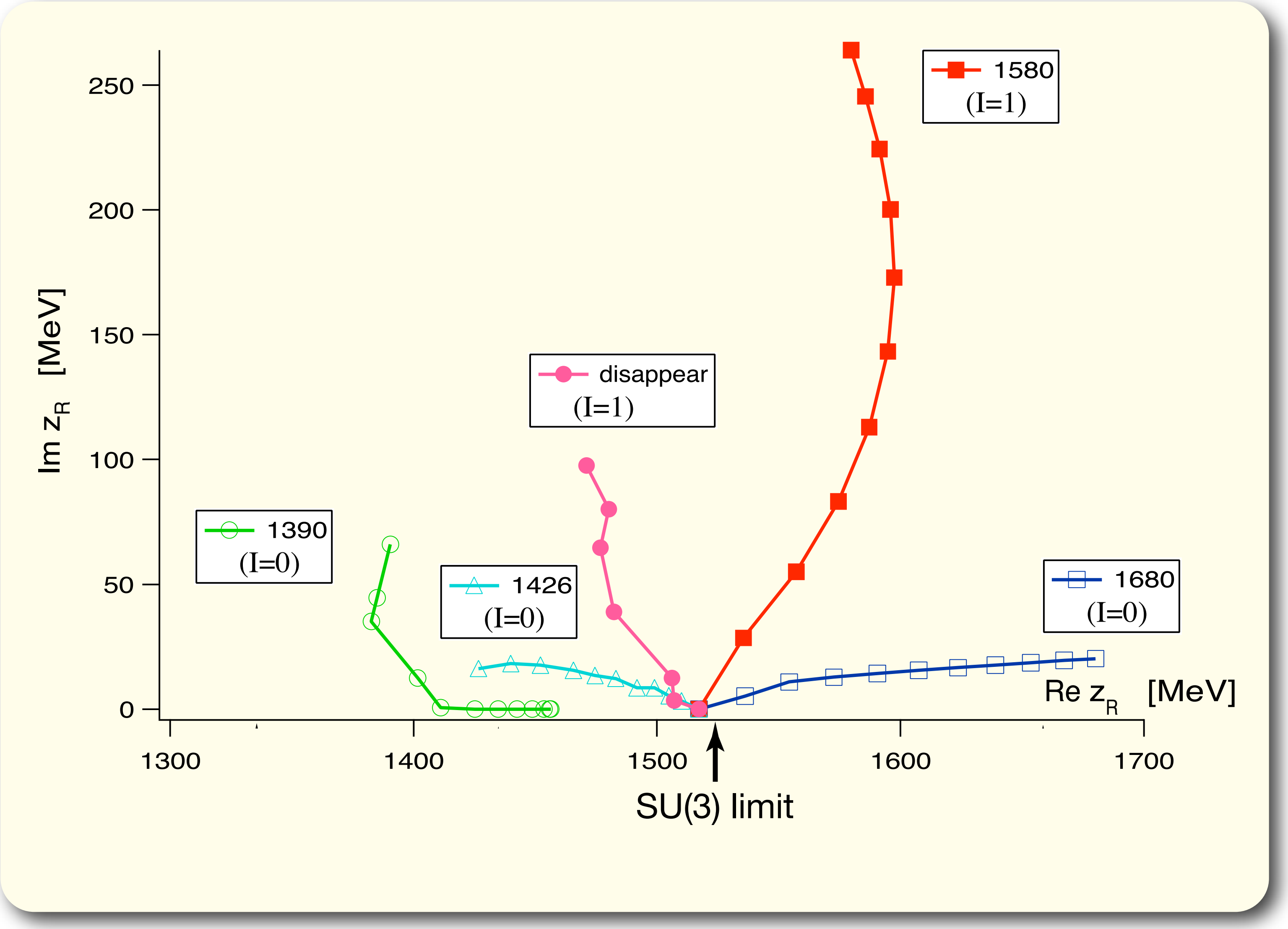
$$B_1 \simeq 70 \ \ \mathrm{MeV}$$
$$B_8 \simeq 5 \ \ \mathrm{MeV}$$

→ learn role of strange quark in hyperon resonances

Thus, knowing the SU(3) breaking effect with systematical studies on the baryon resonance spectra, we can learn role of the strange quark in the structure of the hyperon resonances.

Chiral Symmetry

generation mechanism of resonance



Another interesting point is that this figure gives us a possible picture of the generation mechanism of resonances.

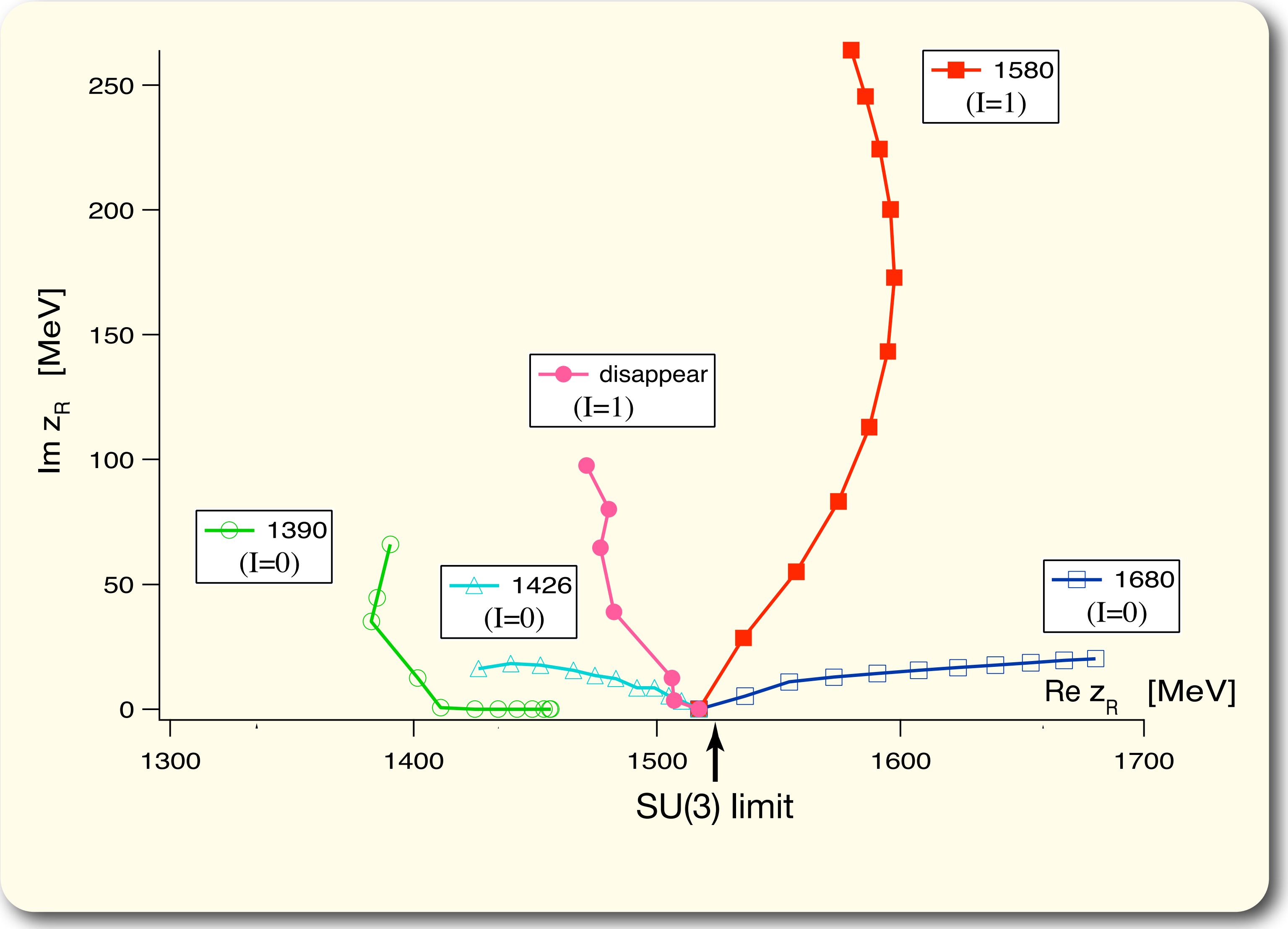
Chiral Symmetry

generation mechanism of resonance

in SU(3) limit

bound states formed

degenerate threshold



In the SU(3) limit, where all the thresholds degenerate, the bound states are formed in the single channel.

Chiral Symmetry

generation mechanism of resonance

in SU(3) limit

bound states formed

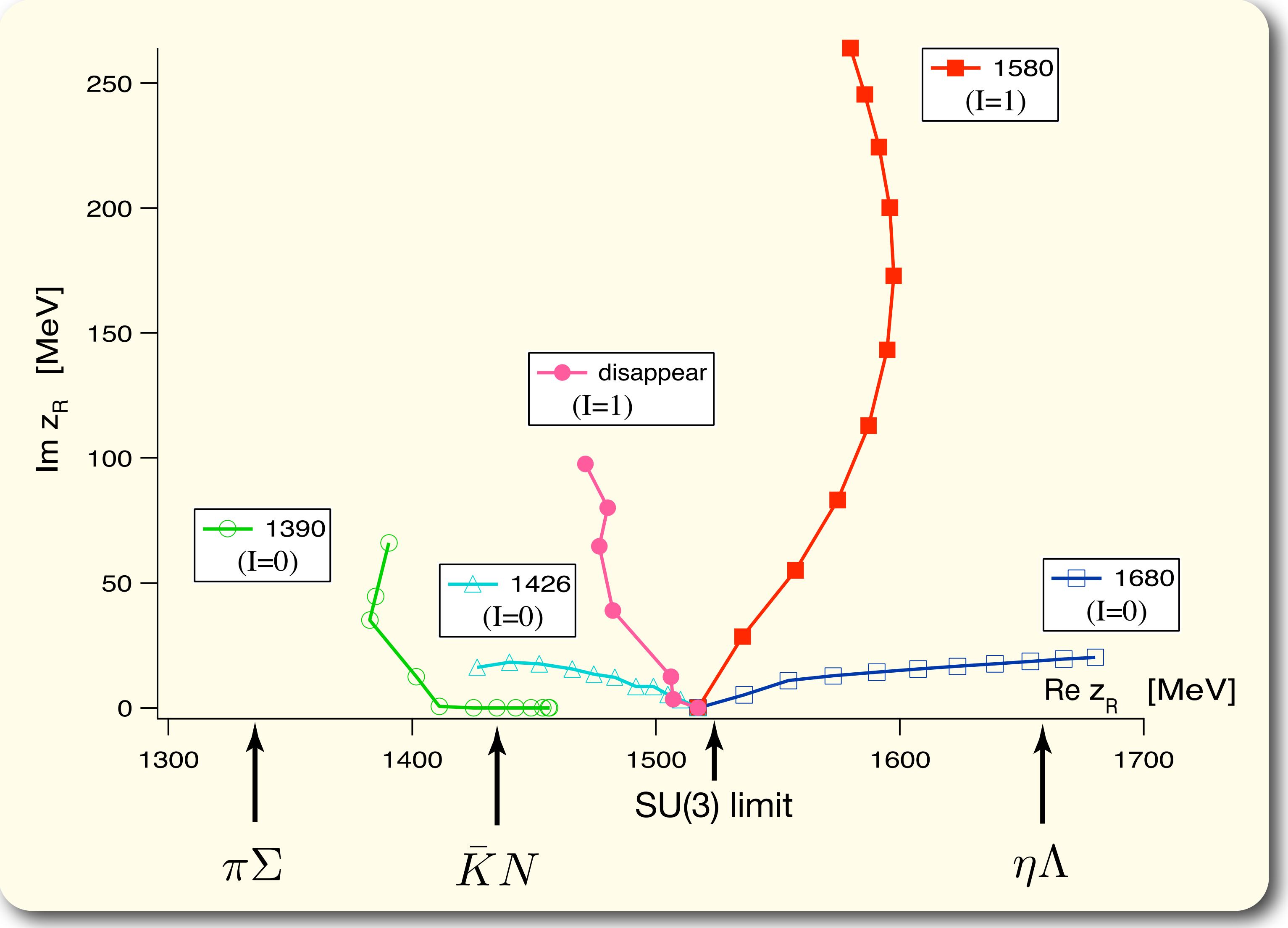
degenerate threshold

with SU(3) breaking

degeneracy of threshold resolved

open decay channels

resonance gets width



With the SU(3) breaking, the degeneracy in the thresholds is resolved. Some of the channels open below the bound states, and the bound states get their decay channel. The bound states become resonances with finite widths.

Chiral Symmetry

generation mechanism of resonance

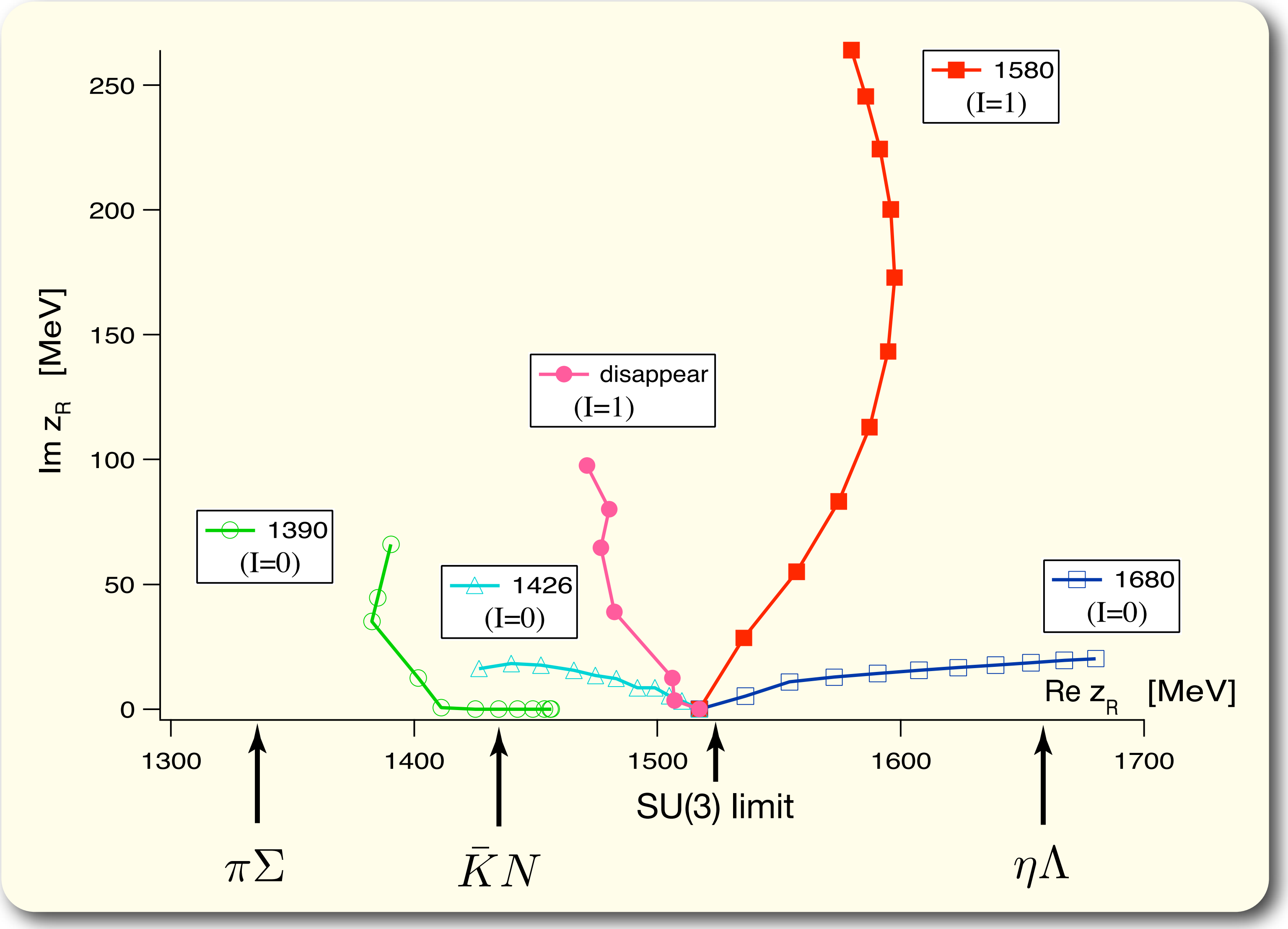
in SU(3) limit

- bound states formed
- degenerate threshold

with SU(3) breaking

- degeneracy of threshold resolved
- open decay channels
- resonance gets width

bound state as a seed of resonance



Namely, enough attraction in the elementary process creates a bound state, then the bound state, as a seed of the resonance, obtains its width due to open channels below the bound state.

Chiral Symmetry

generation mechanism of resonance

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bound states formed

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open decay channels

resonance gets width

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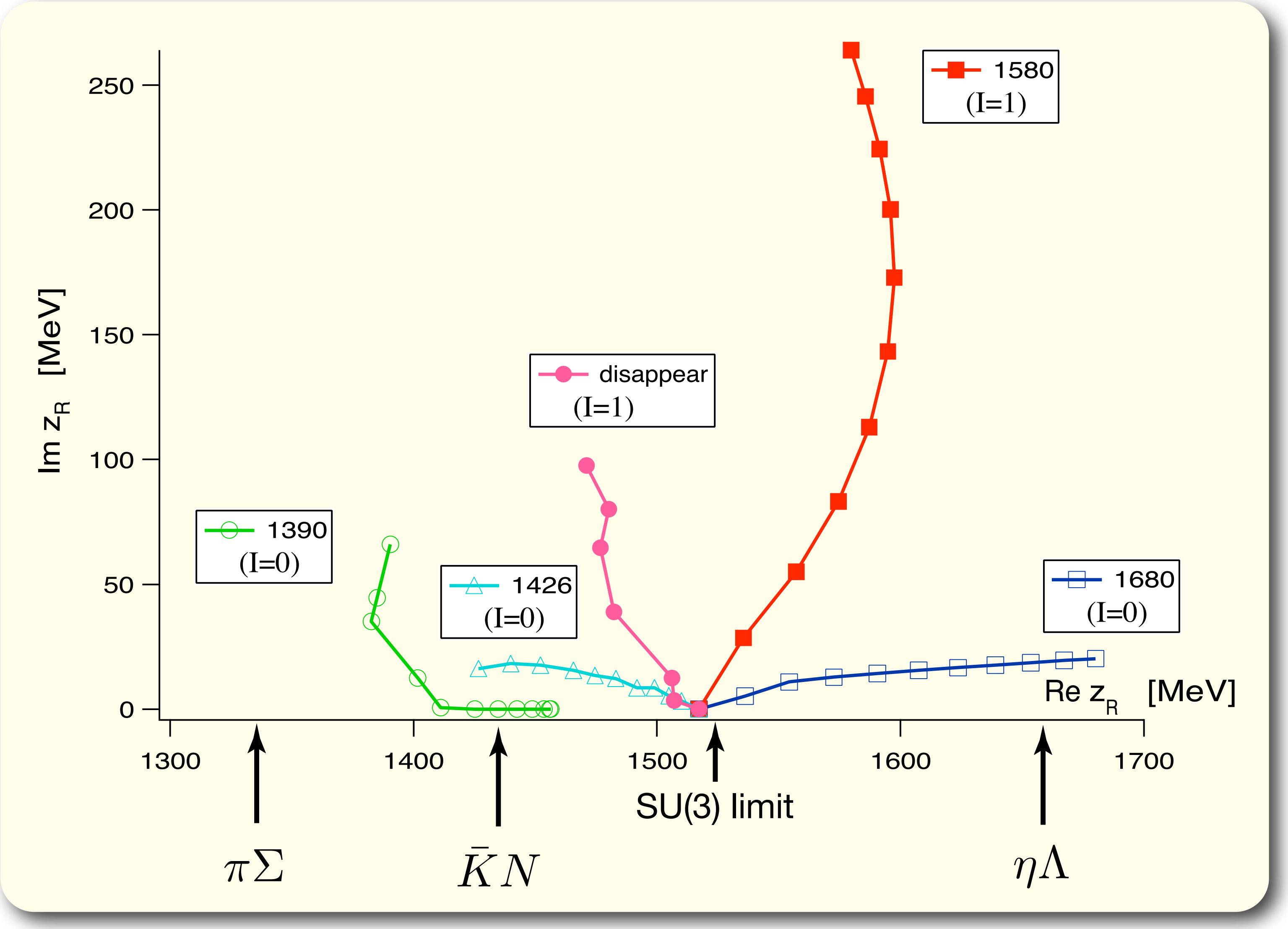


no bound states in chiral limit

In fact, even in the SU(3) limit, whether the bound states can be formed or not depends on the mass of the Nambu-Goldstone boson.

Chiral Symmetry

generation mechanism of resonance

in SU(3) limit

bound states formed

degenerate threshold

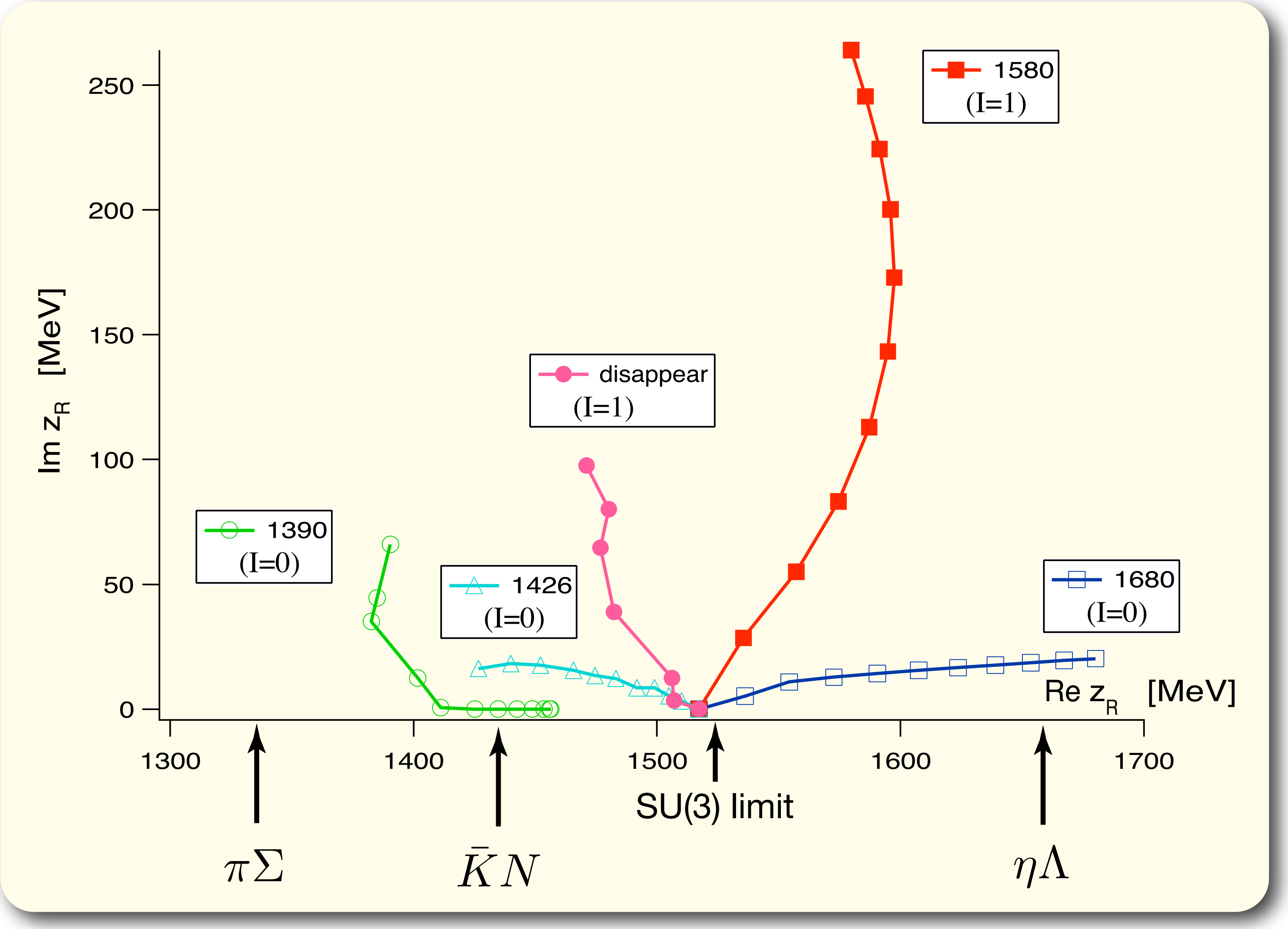
with SU(3) breaking

degeneracy of threshold resolved

open decay channels

resonance gets width

bound state as a seed of resonance



no bound states in chiral limit

With the smaller mass, it is harder to create a bound state with a given attractive coupling, since a meson with a smaller mass escapes more easily from the potential. Actually there are no bound states in the chiral limit.

Chiral Symmetry

generation mechanism of resonance

in SU(3) limit

bound states formed

degenerate threshold

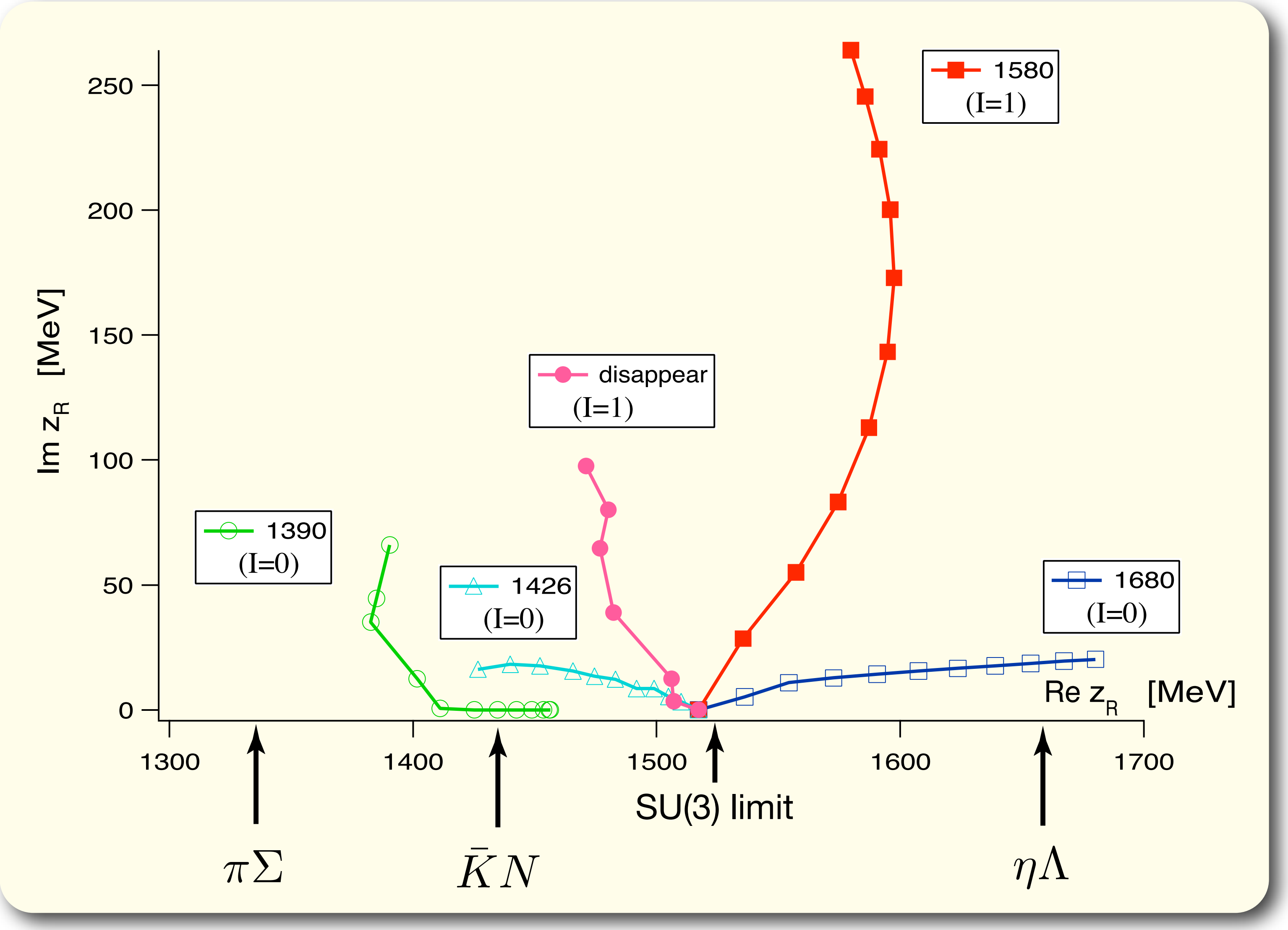
with SU(3) breaking

degeneracy of threshold resolved

open decay channels

resonance gets width

bound state as a seed of resonance



no bound states in chiral limit

the chiral symmetry breaking is essential to generate resonances.

This means that, in the meson-baryon picture, the chiral symmetry breaking is also essential to generate resonances. Thus, the quark mass plays an important role to resonance physics.

Discussion

Symmetry breaking of flavor and chiral symmetries plays important roles.

→ symmetry constraints do not help us
thus further experimental constraints are welcome.

As we have discussed, it seems that symmetry breaking effects of the flavor and chiral symmetries play important roles for the resonance physics. In such situation, symmetry constraints do not help us much, thus further experimental constraints are welcome.

Discussion

Symmetry breaking of flavor and chiral symmetries plays important roles.

→ symmetry constraints do not help us
thus further experimental constraints are welcome.

But this is not bad news...

learn role of the strange quarks and the quark mass in resonances by investigating
what comes from the symmetry properties and
what comes from the symmetry breaking effects.

But this is not bad news, since physics gets richer and richer, and we can learn role of the strange quarks and the quark mass in resonances by investigating what comes from the symmetry properties and what comes from the symmetry breaking effects.

Discussion

Symmetry breaking of flavor and chiral symmetries plays important roles.

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powerful theoretical tools

chiral unitary model, QCD sum rules,
Lattice calculations, quark model approach etc.

Now we have powerful tools for the theoretical investigation on the baryon resonances, such as, chiral unitary model, QCD sum rules, Lattice calculations, quark model approach etc.

Discussion

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chiral unitary approach

masses and widths of the resonances
coupling strengths to channels, also to closed channels

$\lvert g_{ii}\rvert^2$ in particle basis				
Pole	$\bar{K}N$	$\pi\Sigma$	$\eta\Lambda$	$K\Xi$
$1390-66i$	4.5	8.4	0.59	0.38
$1426-16i$	7.3	2.3	2.0	0.13
$1680-20i$	0.62	0.074	1.1	12

Λ channel (S=-1, I=0)

Especially the chiral unitary model is suitable for this purpose, since it describes both the resonances and continuum non-resonant backgrounds. It provides not only the masses and widths of the resonances but also the coupling strengths, even to closed channels.

Discussion

Symmetry breaking of flavor and chiral symmetries plays important roles.

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Λ channel (S=-1, I=0)

If the coupling strengths to closed channels are observed in some indirect productions of resonances, it would give nicer constraints for the theoretical investigation. Ex.) confirmation of the two pole structure of Λ(1405).

Conclusion

In the resonance physics, the explicit breaking of both the flavor and chiral symmetries are essential.

Systematic study on the baryon resonances both

experimentally - providing constraints

theoretically - extracting symmetry breaking effects

will help us for deep understanding of roles of the strange quarks and the quark masses in hadrons.

The baryon resonance physics is hot enough to attract experimentalists and theorists.

Model dependence of pole positions

Original (WT term): pole 1: 1390-66i pole 2: 1426-16i

WT term + Next-to-leading order terms: two-poles

1) C. Garcia-Recio, M. Lutz, J. Nieves (PLB582, 49 (2004))

   pole 1: 1363-115i pole 2: 1409-34i

2) J.A. Oller, J. Prades, M. Verbeni (PRL95,172502 (2005))

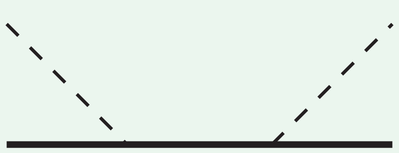
   two poles

3) Borasoy, Nißler, Weise (EPJA25,79 (2005))

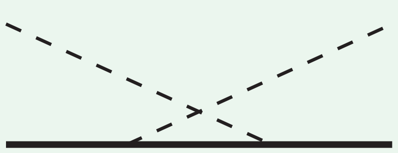
   DEAR data, Kaonic hydrogen

   Next-to-leading order terms
   Elegtromagnetic corrections

	WT (L)	c (NL)
pole 1:	1391-55i	1440-120i
pole 2:	1431-17i	1418-20i
	s	u
	1419-134i	1409-125i
	1418-19i	1419-21i

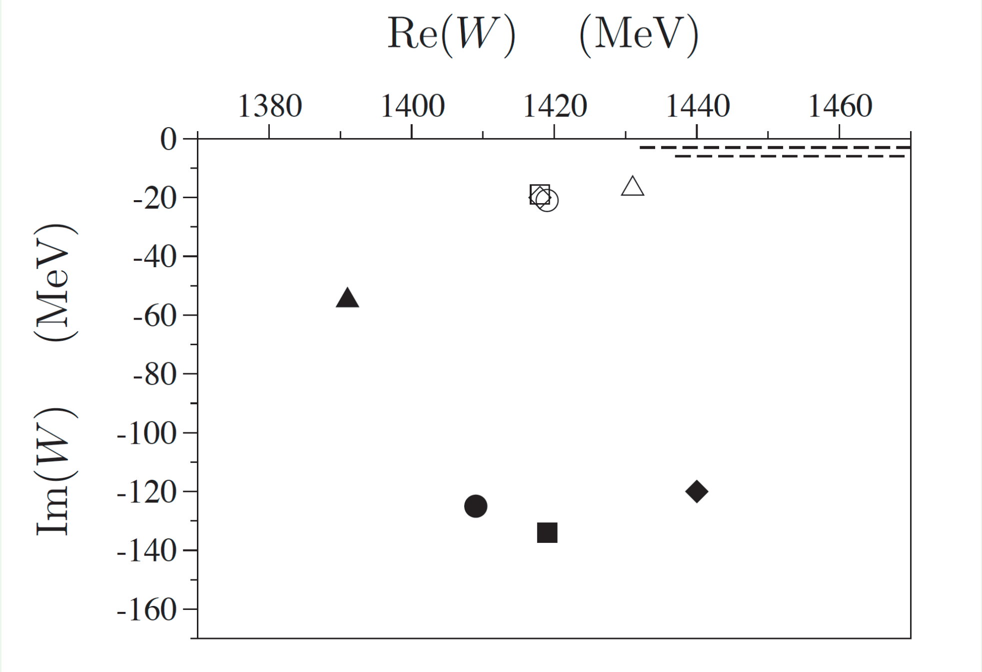


s



u

▲: WT (L) ◆: c (NL) ■: s ●: u



Confirmation of two pole structure

pole 1 : 1390 - 66i strongly couples to $\pi\Sigma$ state
pole 2 : 1426 - 16i dominantly couples to $\bar{K}N$ state

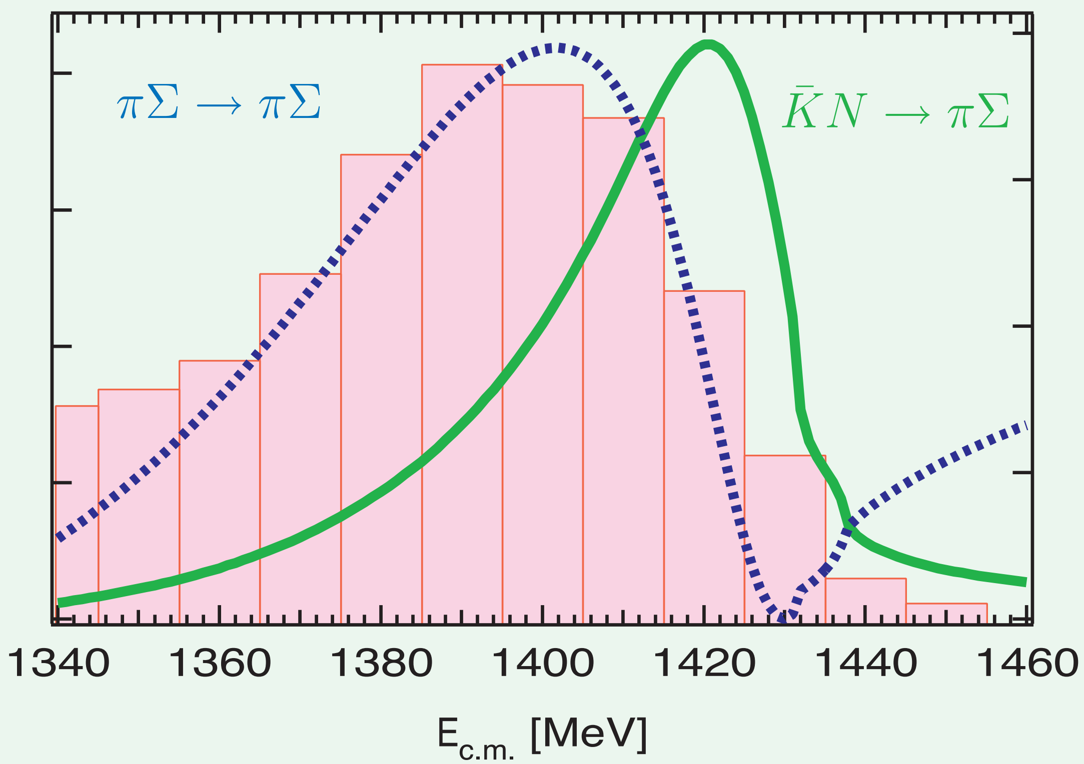
the peak position of the spectrum is

insensitive to channels in the case of 1 pole structure

sensitive to channels in the case of 2 pole structure

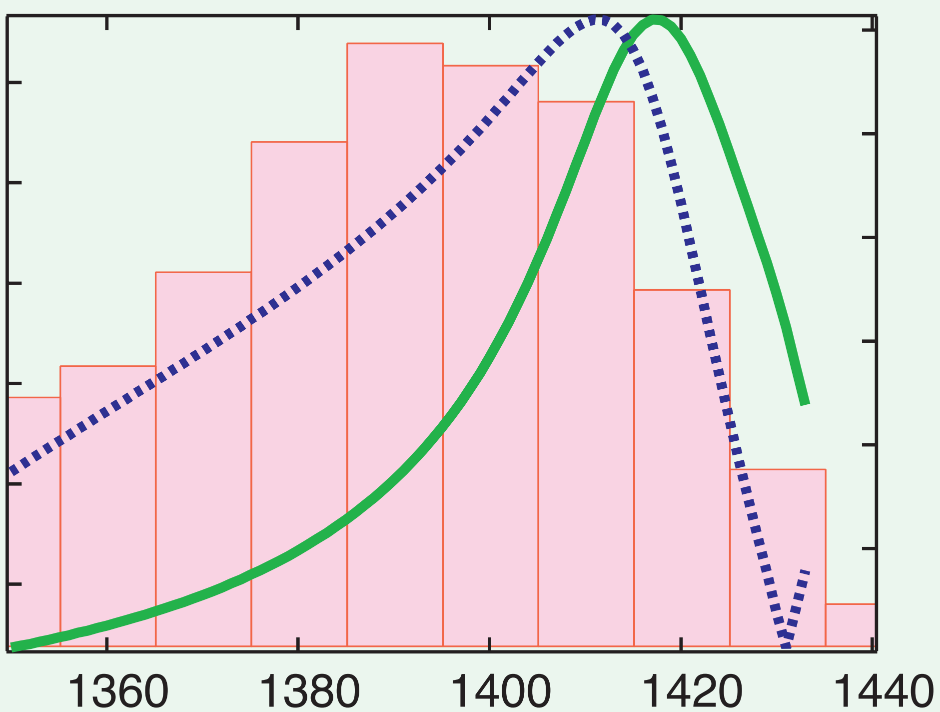
Our model (WT) Two poles

$\pi\Sigma$ Mass distribution



Lutz-Kolomeitsev model (WT+NLO)

Essentially one pole



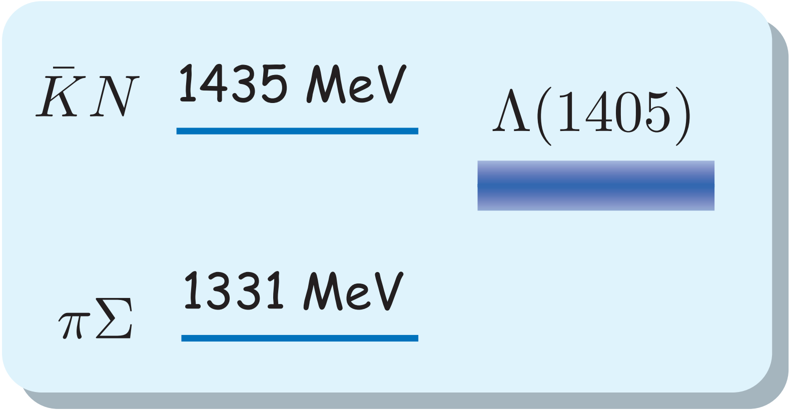
If spectra are fitted by two poles with backgrounds

reproduced by 2 poles **reproduced by 1 pole**

(1 pole fit reproduces PDG value.)

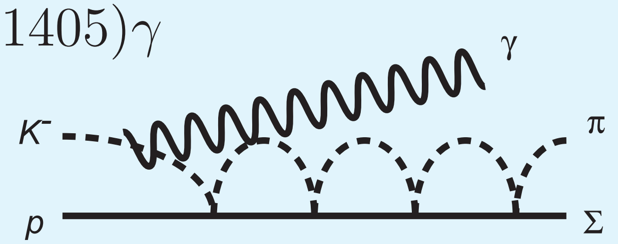
Problem

Both poles below the $\bar{K}N$ threshold



Indirect reaction

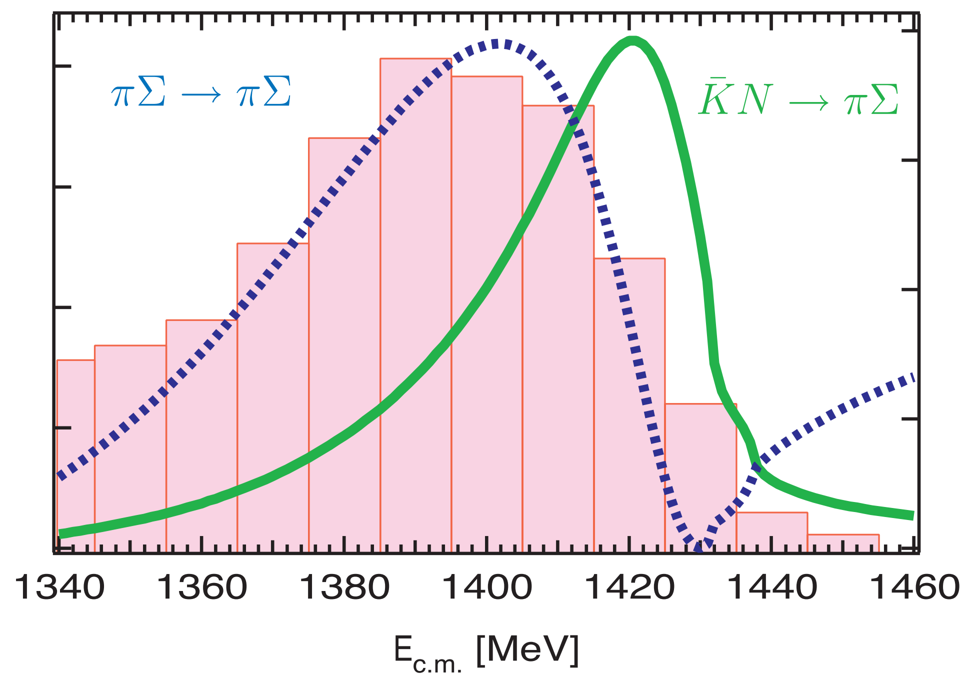
$K^- p \to \Lambda(1405)\gamma$



the Bremsstrahlung loses energy emitting a photon before the creation of the resonances and then the $K^- p$ channel initiates the resonance.

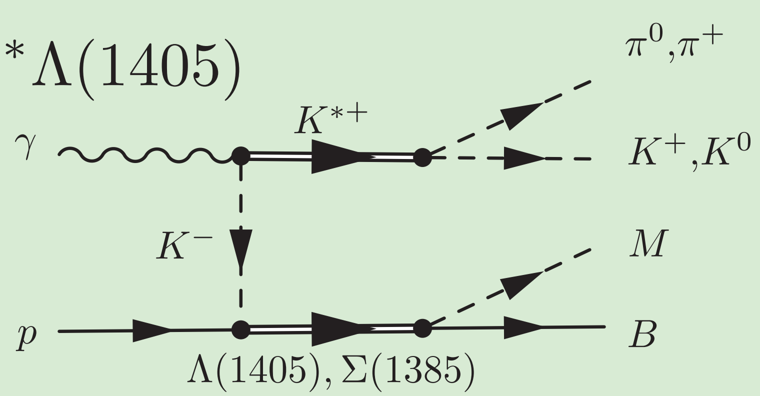
Nacher, Oset, Toki, Ramos, PLB461, 299 (99)

πΣ Mass distribution



K^* photoproduction

$\gamma p \to K^* \Lambda(1405)$



Hyodo, Hosaka, Vacas, Oset, PLB593, 75 (04)